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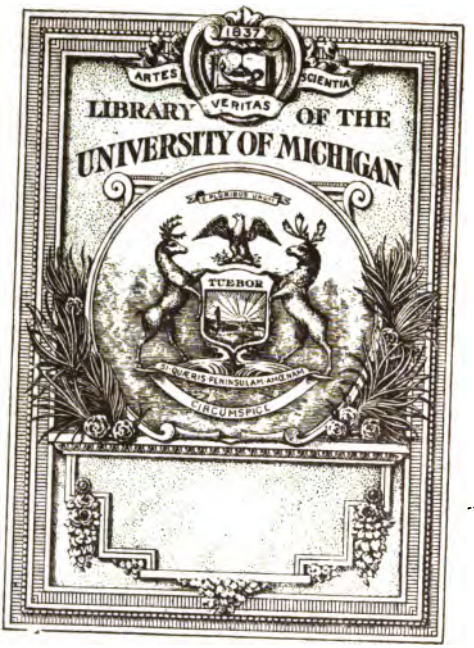
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THE NATURE OF MATTER AND ELECTRICITY

SIR JOSEPH J. THOMSON

(*From the painting in the Cavendish Laboratory*)

Undoubtedly the most eminent living discoverer in the domain of the electrical constitution of matter.

THE NATURE OF MATTER AND ELECTRICITY

AN OUTLINE OF MODERN VIEWS

BY

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PREFACE

This book attempts to give in broad, schematic form the conception of the structure of the material universe which has developed in the minds of modern students of physical science. The treatment of the subject which is here offered is radically elementary, and is intended to be "popular" if not "literary" in its style. But, although elementary, it omits none of the salient general ideas, whether these belong primarily to the sciences of chemistry, electricity, optics, or heat. It is characteristic of the modern standpoint that it permits a blending of all of the physical sciences into a single world view, which grows in unity with the years, and with study. A glance at the table of contents of the present volume will reveal what may seem to the uninitiated reader a very heterogeneous assemblage of topics, but it is the hope of the writers that a perusal of the book itself will give a sense of the profound inner unity of all of these outwardly various matters.

It is the belief of the authors that a book of this nature, written in the light of the most recent discoveries, will find a welcome amongst the scientific laity, as well as with scientific or philosophic workers in general whose special fields are perhaps somewhat removed from that of theoretical physics. At the moment of writing there is no book available dealing with the whole modern theory of matter and energy in either an elementary or an advanced fashion, and treating it as a unit. Many

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admirable treatises on portions of the field are of course obtainable. For a considerably more advanced, yet not very difficult, discussion the reader is referred to three books which together cover the ground fairly thoroughly, *viz.*, The sixth edition of Nernst's "Theoretical Chemistry," the second of Campbell's "Modern Electrical Theory," and Rutherford's "Radio-active Substances and their Radiations." Specific references to other works are given at the end of each Section of Part II of the present book.

Something must be said in explanation of the arrangement of the book. It consists of two parts, the first giving a rapid survey of the entire subject, outlining the fundamental conceptions and emphasizing their most significant applications only, while the second retraces the same general field in a slower and less connected way, in order to consider details *omitted* in the more cursory treatment. The second part is divided into fifty-six sections, each of which is numbered and referred to by its number in the appropriate connection in Part I.

The book may be read in various ways according to the purposes or pleasure of the reader. If he is interested only to acquaint himself with the fundamentals of the modern theory through a quick, general sketch he may read Part I continuously and omit Part II altogether. If, on the other hand, he is already familiar with these essentials he may prefer to reverse the procedure and omit Part I. Part II although definitely divided by topics nevertheless forms a fairly continuous discussion. In general, however, the best method of using the book will probably be to read both of the sections in parallel, referring to each Section in Part II as its number appears in the text of the first part. It is believed that this method of study will encourage the type of attitude which is re-

quired to give the subject the greatest clearness in the reader's mind. It is obvious that the structure of Part II permits its ready use for purposes of special reference, such as may arise, for example, in connection with school courses in elementary physics and chemistry.

The basis of Part I is to be found in a series of articles contributed in 1911 by D. F. Comstock to the "Science Conspectus," the journal of the Massachusetts Institute of Technology Society of Arts. Somewhat to his surprise, there was a wide demand from various sources for further copies of these articles, and hence it seemed worth while to publish them in book form, together with a more complete discussion of the same subject. The articles have been amplified and brought up to date by their original author.

At Professor Comstock's suggestion, I undertook the writing of Part II, which provides the more elaborate treatment just mentioned.

L. T. TROLAND

Boston, Mass.

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PART I

A BRIEF OUTLINE OF THE MODERN THEORY OF MATTER, ELECTRICITY, AND ENERGY

CHAPTER I

INTRODUCTORY

During the last two decades there has been a very great advance in our knowledge of the ultimate constitution of matter. (1) The older ideas which prompted the contemptuous phrase "gross matter" are inadequate to represent the extraordinary complexity and delicacy of structure which have since been revealed. The end is of course not yet, but throughout all this advance there has been singularly little in former ideas which had to be considered totally wrong. They were right as far as they went, although insufficient, and so it probably is with our present ideas respecting the structure of things; they will doubtless appear crude in the light of future knowledge but in a general way they are probably right as far as they go, and hence are worthy of our attention.

CHAPTER II

THE ULTIMATE REALITIES

According to the modern theory of matter all bodies are complex structures composed of small particles called

NOTE: The full-face numbers inserted in the text at various points refer to the Sections of Part II in which related subjects are discussed (see Preface), or in which further details are given on the same subject.

atoms, together with still smaller particles known as *electrons*. If, therefore, we were familiar with the laws of action of atoms and electrons we should understand completely all the physical phenomena in nature. The atom, as we shall see later, is a much more complex structure than the electron, so that atoms and electrons are not quite on a par as regards classification, except from the introductory point of view, from which we begin discussion.

As a third fundamental entity, there should be mentioned the *energy* associated with atoms and electrons, but for the present this will be left out of consideration.

CHAPTER III

ATOMS AND THEIR BEHAVIOR

Size. — Atoms are minute particles each about one three-hundred-millionth of an inch in diameter (2). If the earth were made up of base-balls it would be a fair model of a drop of water made up of atoms. The most powerful microscope known, used under the best conditions, would enable us to see an object approximately two hundred atoms in width. Single atoms are, therefore, totally invisible, and their properties cannot be found out by direct inspection (3).

Shape. — Not much is known as regards the shape of the atoms, but in general they behave as if they were not very far from spherical (4).

Different Kinds. — We are now acquainted with about one hundred different kinds of atoms, that is, different species. The individual atoms in each species are, however, exactly alike, or have so nearly the same properties that under most conditions there is no difference in the

action of the individuals. Atoms of different kinds differ in size and still more in weight.

At present there is no agreement as to the difference in size of the various kinds of atoms. On the basis of certain calculations from coefficients of expansion, some

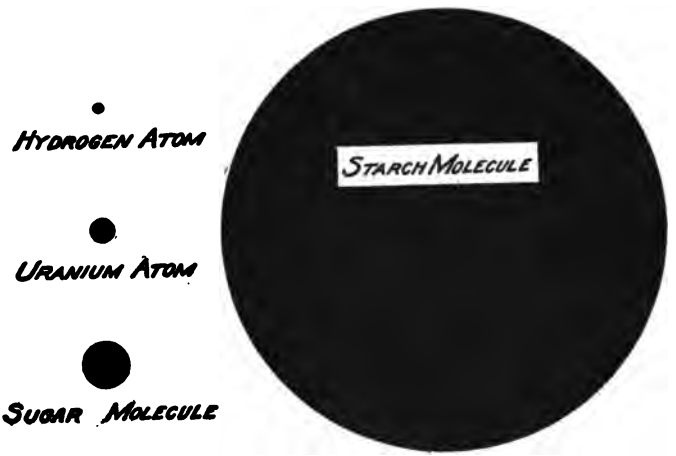


Fig. 1

THE RELATIVE SIZES OF ATOMS AND MOLECULES

This diagram is intended to give an idea of the relative magnitudes of atoms and molecules. However, the drawings are only symbolic, as the dimensions have been calculated on the assumption that the molecules are spherical, which cannot be strictly true. It will be noticed that the smallest atom (that of hydrogen) differs only slightly in size from the largest atom (that of uranium). The starch molecule is probably one of the largest which exists and it will be seen that, according to the diagram, it is very much larger than the largest atom or than the molecule of sugar. The relative weights of the particles represented are as follows: Hydrogen, 1; Uranium, 239; Sugar, 346; and Starch, not accurately known but probably about 25,000. A molecule of ordinary alcohol weighing 46, would be slightly larger than the uranium atom.

investigators believe that the sizes of the different kinds of atoms are in the same order as their weights. According to this view, therefore, the lightest atom, hydrogen, is also the smallest; and the heaviest atom, uranium, is also the largest. The atom of uranium is about 240 times as heavy as the atom of hydrogen, whereas it has

only about two and one-half times as great a diameter. If this view is correct, we might represent an atom of hydrogen by a wooden ball the size of a pea, and an atom of uranium by a lead ball the size of a cherry. Representatives of all of the other atomic species would then be arranged in a complete series from the small wooden ball to the large lead one.

Fig. 2

RELATIVE SIZE OF MOLECULES AND VISIBLE PARTICLES

The molecule represented in this diagram is the starch molecule of Figure 1, very much reduced in scale. It is not certain that the starch molecule is the largest which exists, but it is very far from being the smallest. The microscopic particle which is represented is the smallest which can actually be seen under the most powerful microscope. Particles nearly as small as the starch molecule can be seen indirectly by means of the ultra-microscope. (See Section 3.)

Although the individual atoms of one kind are, with certain modern reservations, all alike, those of different species have decidedly different properties, and this difference in property is what gives variety to the physical world as we see it. The atoms of one species are

Fig. 3

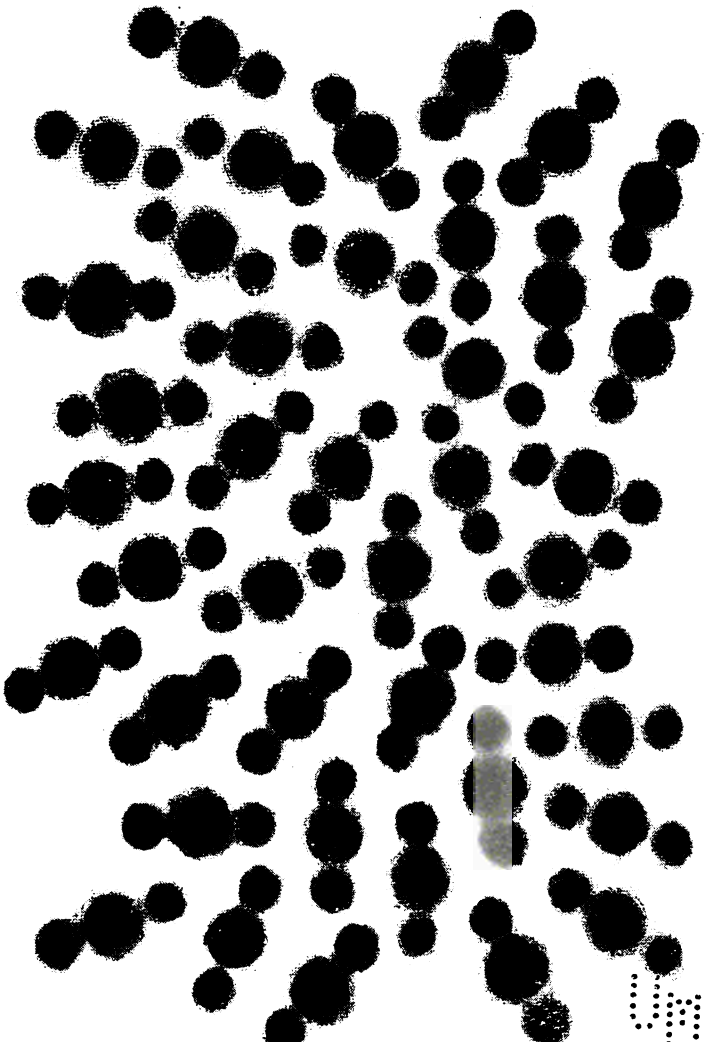
WATER MOLECULES

An instantaneous view of a liquid compound, i.e., a substance the molecules of which consist of more than one kind of atom. The above would be a fair representation of a portion of water a few hundred-millionths of an inch in width. The water molecule consists of one oxygen atom combined with two hydrogen atoms. The only difference between the above and the liquid element (say oxygen) of Figure 6 is in the structure of the molecules, as already explained. This makes all the difference in the world, however, in the properties of the two substances. The atoms of oxygen, when alone as a liquid element, do not attract each other enough to form a liquid except when the vibration is very little indeed, i.e., at a very low temperature. At ordinary temperatures oxygen, therefore, is a gas like that of Figure 8. The water molecules have, however, enough attraction for each other, so that at ordinary temperatures they remain near one another as a to constitute a liquid.

Fig. 3

WATER MOLECULES

An instantaneous view of a liquid compound, *i.e.*, a substance the molecules of which consist of more than one kind of atom. The above would be a fair representation of a portion of water a few hundred-millionths of an inch in width. The water molecule consists of one oxygen atom combined with two hydrogen atoms. The only difference between the above and the liquid *element* (say oxygen) of Figure 5 is in the structure of the molecules, as already explained. This makes all the difference in the world, however, in the properties of the two substances. The atoms of oxygen, when alone as a liquid element, do not attract each other enough to form a liquid except when the vibration is very little indeed, *i.e.*, at a very low temperature. At ordinary temperatures oxygen, therefore, is a gas like that of Figure 8. The water molecules have, however, enough attraction for each other, so that at ordinary temperatures they remain near one another and so constitute a liquid.



so definite, unique, and characteristic in their actions and properties that they give one the impression of a delicacy and complexity of structure suggestive, almost, of the complexity of personality. There are subtle resemblances between one species and another with regard to one property, and marked differences with regard to another (6). Hence one should be very careful to realize that when, for reasons of analogy, we represent an atom as a ball of wood or a ball of lead we are representing it only in the vaguest general way, and are totally ignoring its complexity and individuality.

Tendency to Form Groups (Molecules). — Atoms tend to form groups known as molecules. The atoms in a molecule adhere with considerable force and some molecules can be broken up only with the greatest difficulty. These groups have a definite individuality and unless acted on from the outside they are apparently permanent. The same atoms may be grouped into quite different molecules just as the same bricks may be used to build a church or a jail, or the same letters used to form altogether different words. The individuality of a molecule is perhaps best appreciated by thinking of the individuality of a word. A word, though consisting solely of letters, has a definite unity of its own. A molecule made up of atoms is just as definite an aggregate (7).

As a help toward a concrete conception two drawings are given in Figures 3 and 4. The first represents symbolically water molecules, each consisting of two hydrogen atoms and one oxygen atom, in the closely crowded state known as liquid, and the second the same molecules in the more dispersed state known as vapor (steam).

Elements and Compounds. — When the atoms making up the molecules of a substance are all alike, that is when

they belong to the same species, the substance is called an "element." An element, therefore, is composed of only one kind of atom. A compound is a substance the molecules of which are made up of more than one kind of atom.

Figure 5 represents symbolically a liquid element, Figure 3 a liquid compound. "Oxygen," "hydrogen," "carbon," "lead," "copper," are names of some of the elements, and *they are, therefore, names of atomic species.* "Water," "salt," "sugar," and "carbon-dioxide" are names of compounds, and hence are the names of molecular species.

The water molecules in Figure 3 are seen to consist of one large atom and two smaller ones in a group. The large atom is an oxygen atom. The two smaller ones are hydrogen atoms and the group as a whole is a water molecule. It is therefore true to say that a water molecule is the smallest particle of water that it is possible to have, for if it is further broken up it is no longer water. These drawings are in no sense other than symbolic.

As a moment's thought will show, thousands upon thousands of different kinds of molecules are known. Some, such as the water molecule, are relatively simple and composed of a few atoms, and some, such as the sugar molecule, are very complex. (See Figure 6.) In the particular case of the sugar molecule the number of atoms is forty-five.

A small crystal of "granulated" sugar is, therefore, a solid mass consisting of hundreds of millions of sugar molecules, that is hundreds of millions of definite, coherent groups of atoms, each group containing twelve atoms of carbon, twenty-two of hydrogen, and eleven of oxygen.

Fig. 4

MOLECULES OF STEAM

An instantaneous view of water vapor or other gaseous compound. To form the above it is merely necessary to heat, i.e., increase the vibration of the ordinary water of figure 3, until the attraction of the molecules for one another is overcome and they fly in all directions. The only difference between the above and the gas of Figure 8 is that the molecules there are composed of two identical atoms while here they are not. That is an element; this is a compound.

Fig. 4

MOLECULES OF STEAM

An instantaneous view of water vapor or other *gaseous compound*. To form the above it is merely necessary to heat, *i.e.*, increase the vibration of the ordinary water of Figure 3, until the attraction of the molecules for one another is overcome and they fly in all directions. The only difference between the above and the gas of Figure 8 is that the molecules there are composed of two identical atoms while here they are not. That is an element, this is a compound.

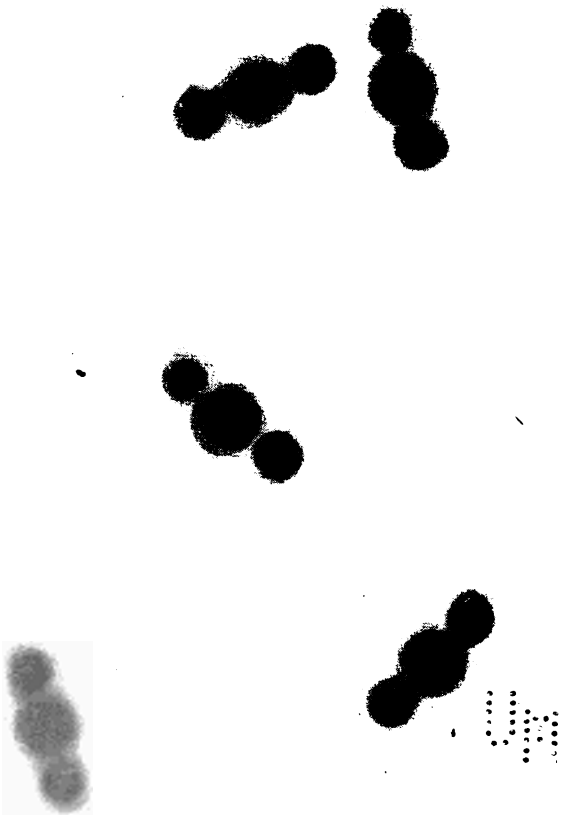


Fig. 5

ATOMS OF A LIQUID

An instantaneous view of a portion of liquid, such as mercury, liquid oxygen, or any melted metal a few hundred-millionths of an inch wide, as seen through an enormously powerful microscope of enormous power. The atoms are in constant, violent vibration, this vibration being what we call heat. The "temperature" is a measure of the violence of the vibration. In other words when we "heat" a substance we increase the violence of the atomic vibration.

The minute black points shown in a few places between the atoms are "electrons." These are very small particles, charged with negative electricity. They are constantly being knocked out of the atoms by the violence of the (heat) vibration and are constantly going back in again. The number which are "free" at any one time depends on the kind of atoms which make up the substance. In metals there are almost as many free electrons as there are atoms. In other substances there are very few. The electrons exist, it is thought, in large numbers within the various atoms. In size the electron is extremely small compared with an atom, the relative magnitudes being about one to one-hundred thousand, so that even the black points in the drawing enormously exaggerate their size compared to the atoms. The electrons are all alike.

Fig. 5

ATOMS OF A LIQUID

An instantaneous view of a portion of liquid, such as mercury, liquid oxygen, or any melted metal a few hundred-millionths of an inch wide, as seen through an *imaginary microscope* of enormous power. The atoms are in constant, violent vibration, this vibration being what we call heat. The "temperature" is a measure of the violence of the vibration. In other words when we "heat" a substance we increase the violence of the atomic vibration.

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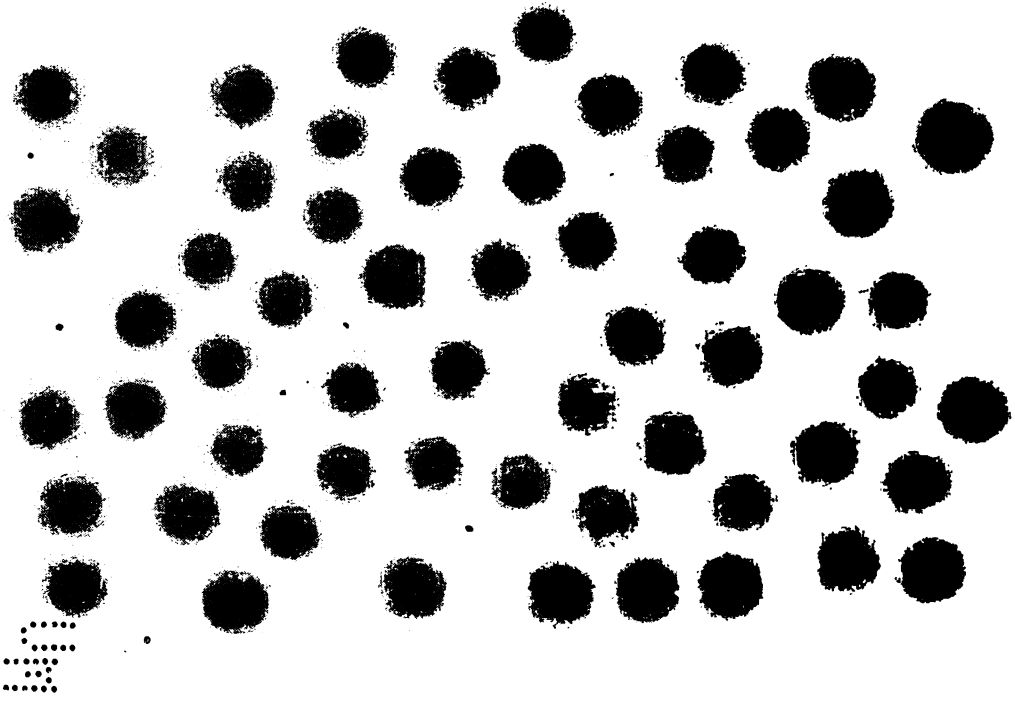


The definiteness of molecular structure must not be forgotten. One of these sugar molecules might be compared to a word of forty-five letters, for if a single atom were removed from the group, or if a single atom had its position markedly changed, the group might still be a molecule, but it would not be a molecule of sugar, and a vast mass of such modified molecules would not make up a crystal having the same properties as the one with which we started (8).

Chemical Action. — Chemical action is the name given to the process in which the groups known as molecules are either formed or destroyed. When a substance is burned or when an acid "eats" a metal the action involves the formation of new molecules, because of the rearrangement of the atoms, and therefore the production of new substances. By an inspection of Figure 3 it will be clear that if two of the "large" oxygen atoms could be separated from their respective water *molecules*, to recombine as represented in Figure 8, there would be left behind, four of the "small" hydrogen atoms of Figure 3 (two from each decomposed molecule), and these would adhere in twos and would form two hydrogen molecules. When thousands of molecules were thus broken up the complete process would be called the decomposition of water into oxygen and hydrogen. It is easily accomplished in the laboratory.

It is clear that when complex molecules are present it is possible for the rearrangement which takes place to be very complicated indeed. There are often, also, several possibilities of rearrangement, each resulting in a different set of substances as a final outcome.

Outside conditions such as temperature, pressure, etc., have marked effects on the results of chemical reactions.

Chemical action, therefore, always implies the break-

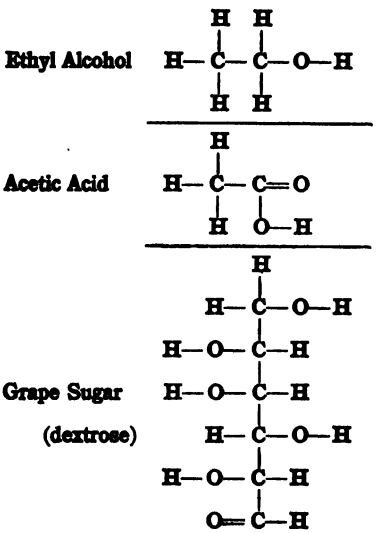


Fig. 6a

FORMULA OF SOME COMMON ORGANIC COMPOUNDS

NOTE. — The formula of ordinary cane sugar (or saccharose) is not definitely established, but probably consists of two groups of atoms similar to that for dextrose, combined with a molecule of water.

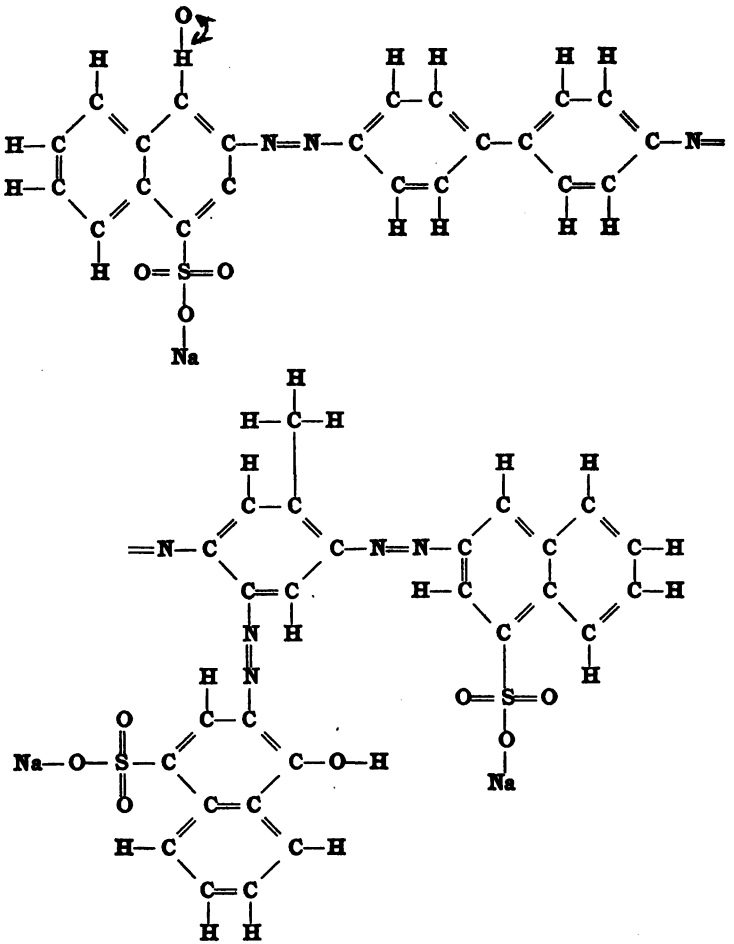


Fig. 6b

FORMULA OF AN AZO-DYE

NOTE. This formula is divided into two parts because of exigencies of space, but in reality represents a single structure.

ing up or forming of molecules, and in general it means both (9).

Permanence of the Atom. — Although every one of the thousands of "chemical reactions" which are daily going on in the world involves the formation or decomposition of *molecules*, no way has yet been found to change an atom of one species into one of another species. To find such a way was the hope of the alchemists but it was never realized. We shall see later that the atoms are probably not absolutely permanent but that the mysterious forces which preserve their integrity are so much greater than the forces which hold them together in molecules, that as yet it has not been found possible to shatter them artificially.

The atoms have great family attraction and it is the business of the chemist to make use of this attraction in the service of man, but the instinct, we might say, of self-preservation is so vastly greater in the atom than its group-forming tendency, that although it submits to the breaking of family ties it will not allow its own individuality to be tampered with.

To state that it will never be possible to break up atoms artificially would of course be folly, but we can say at present with considerable certainty that the disruption of atoms must involve forces of an entirely different magnitude from those called "chemical," which are associated with the breaking up of molecules into atoms.

We shall see later that there appears to be going on in nature a spontaneous decomposition of the atoms of radium and certain other substances, but thus far it has been found quite impossible artificially to influence this spontaneous disruption to the slightest degree, and therefore although we might call the process "natural al-

Fig. 7

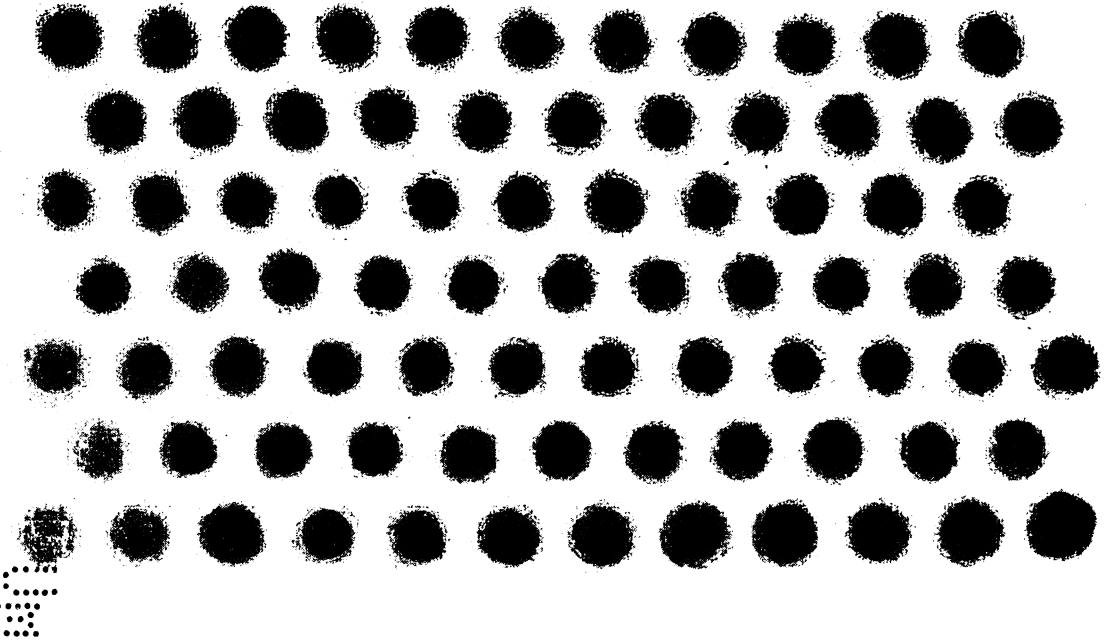
ATOMS OF A SOLID

An instantaneous view of a bit of a solid substance, such as solid mercury, iron, or copper a few hundred-millionths of an inch wide, as seen through an imaginary microscope of enormous power. The atoms are in rapid vibration as in the liquid of Figure 6. They are, however, nearer together and their vibration is less violent. In Figure 6 and Figure 7 represent the same substance in the liquid and the solid states respectively, then 6 passes into 7 by cooling, *i.e.*, by reduction of the vibration known as heat. This lessening of the vibration enables the attraction of the molecules for each other to pull them nearer together. When near enough together they suddenly assume an orderly arrangement like children's blocks, as shown in Figure 7, and the whole material particle, therefore, becomes rigid. The liquid of Figure 6 is then said to have "frozen." The above is fairly representative of any solid element, *i.e.*, any solid composed of only one kind of atoms. Many substances which we call solid probably lack the orderly arrangement of atoms shown above and, on the other hand, some liquids possess it. The distinction between liquid and solid is that in the former case the vibration is so intense that any permanent position of an atom is impossible and it is free to move around among the other atoms, while in the latter (solid) the vibration is relatively less and each atom remains in the same general locality closely held by the attraction of the others.

Fig. 7

ATOMS OF A SOLID

An instantaneous view of a bit of a solid substance, such as solid mercury, iron, or copper a few hundred-millionths of an inch wide, as seen through an *imaginary microscope* of enormous power. The atoms are in rapid vibration as in the liquid of Figure 5. They are, however, nearer together and their vibration is less violent. If Figure 5 and Figure 7 represent the same substance in the liquid and the solid states respectively, then 5 passes into 7 by *cooling*, *i.e.*, by reduction of the vibration known as heat. This lessening of the vibration enables the attraction of the molecules for each other to pull them nearer together. When near enough together they suddenly assume an orderly arrangement like children's blocks, as shown in Figure 7, and the whole material particle, therefore, becomes rigid. The liquid of Figure 5 is then said to have "frozen." The above is fairly representative of any solid element, *i.e.*, any solid composed of only one kind of atoms. Many substances which we call solid probably lack the orderly arrangement of atoms shown above and, on the other hand, some liquids possess it. The distinction between liquid and solid is that in the former case the vibration is so intense that *any* permanent position of an atom is impossible and it is free to move around among the other atoms, while in the latter (solid) the vibration is relatively less and each atom remains in the same general locality closely held by the attraction of the others.



chemy" it cannot be called alchemy in the ordinary sense of the word.

General Forces of Attraction. — Just as atoms have forces of attraction which hold them together in molecules, so molecules attract each other and tend to form the large aggregates which we call "objects." These forces are in general weaker than the forces between the atoms (10). They are great enough, however, to account for the relatively strong cohesion of solid bodies and the weaker cohesion of liquids.

CHAPTER IV

THE NATURE OF HEAT AND ALLIED PHENOMENA

The Motion of the Molecules. — It is now believed, and the odds amount almost to certainty (11), that all atoms of all substances are in ceaseless motion to and fro. This motion is what we call the heat of a body.[1] The more violent the motion the hotter the body (12). It is perhaps a pity that the motion picture art is not developed to a point which would enable us to embody this violent vibration in the accompanying figures, so we must request imagination to aid incompetent art and to endow every atom or molecule of Figures 3 to 8 with a rapid motion; a motion which, like the modern idea of freedom, is limited only by the equal rights of all the other atoms.

Thus in the liquid and solid states (Figures 3, 5 and 7) the crowding is so close that "the rights of others"

[1] Strictly speaking, it is the *energy* of the atomic or molecular motion which constitutes the heat of a body. The distinction between atoms, molecules and electrons is not important when heat phenomena are being described in a general way since it is probable that all of the particles share in the motion.

allow only vibration through a very limited distance, while in the gaseous state (Figures 4 and 8), the motion consists of a straight line flight until by chance there is an encounter with another molecule. When this occurs there is a rebound and then another flight. The distance between the molecules is so small and their speed is so large that literally billions of these impacts are occurring every second in even a cubic inch of gas (13).

Molecules Have No Friction. — It is necessary in order that this motion should continue indefinitely that the atoms or molecules[1] be considered frictionless. At first sight this seems an improbable hypothesis, but when the nature of friction is understood from the present point of view the assumption is seen to be justified. A number of billiard balls put on a table and set going would bound to and fro for a short time and gradually come to a stop, but this is because at every impact part of the energy of the balls' motion is wasted in the form of heat, that is, the balls are actually a trifle warmer after striking each other than before. Now from the present point of view, as we have just seen, "warmer" means more rapid molecular motion, so that the billiard balls gradually slow down and stop *because* their motion is gradually transformed into the invisible motion of the molecules which compose them and surrounding objects. Thus friction exists between visible objects solely because of the existence of the molecules which go to make them up, these molecules absorbing the motion.

From this it is clear that for two molecules to waste energy in impact after the manner of two billiard balls,

[1] The argument here presented applies strictly only to the "ultimate particles" of matter, whatever these may be. However, no very important inaccuracy can result from identifying these ultimate particles with atoms, molecules and electrons.

it would be necessary for them to be composed of still smaller "molecules." Hence, the ultimate particles themselves cannot possess friction in the ordinary sense.

As a matter of fact we shall see later that molecules *do* lose energy, not in a way similar to the friction of large objects, but by radiating it in the form of heat waves. An analogy for this radiation of energy may still be found among billiard balls, for if they, the table, the cushions against which they strike, and the air around, were all perfectly elastic and frictionless, the balls when set going would keep their motion for a far greater time than they actually do, but they would not continue to move indefinitely. This is because at each impact between two balls there would still be a *sound*, the "crack" with which we are all familiar, and this would carry energy away. This loss of energy by sound is vaguely similar to the *radiation* of heat energy by the molecules of a substance (15).

Solid, Liquid and Gas. — All substances which do not decompose (that is, all substances the molecules of which do not break up) on heating, are capable of existing in three states, the *solid*, the *liquid* and the *gaseous*. A solid when heated above its melting point becomes a liquid and a liquid through the process of evaporation or boiling changes into a gas. It is also possible, at certain temperatures and pressures, for a solid to pass directly into the gaseous state and *vice versa*.

From the present point of view the cause of these changes is readily seen. We have said that heating a body means increasing the violence of its internal vibration. Now it is easy to imagine that when in a solid substance this vibration comes to exceed a certain amount the atoms or molecules will no longer be able to adhere in orderly arrangement but will be forced farther apart

by the motion and, although not completely out of the influence of each other's attraction so that they become totally dispersed, still are so far apart that they wander about at random, like the frantic members of a mob. Under these circumstances rigidity no longer exists and the substance is liquid (16).

When the vibration gets still more violent, *i.e.*, when the liquid is further heated, the number of molecules at the surface of the liquid which escape into the surrounding region becomes very large. The molecules which escape do so because amid the random vibration they happen to have a speed sufficient to carry them up beyond the attraction of the other molecules of the liquid. These molecules in the space above the liquid constitute a gas (17).

In the case of a solid or liquid the heat motion takes place through a very short distance and is then reversed, and therefore we may speak with propriety of the motion as a "*vibration*" of the molecules or atoms. In the case of a gas, however, the motion is different, each molecule travelling practically in a straight line until by chance it encounters another flying molecule. In such a gas as air (which is mainly a mixture of oxygen gas and nitrogen gas) a molecule travels on the average through a distance several hundred times its own diameter before it strikes another (14).

The existence of this atomic and molecular motion is at the very heart of the modern conception of matter. A somewhat extended analogy will, therefore, not be out of place.

Suppose that into a room are thrown at high speed, through an open door, ten thousand tennis balls, and that the door is then closed. It is clear that the balls will for a time bound back and forth among themselves, striking

the walls and each other. If, now, we make the ideal assumption that the walls of the room and the balls are perfectly elastic, that is, that there is no energy lost at any of the impacts, it is clear that the bouncing of the

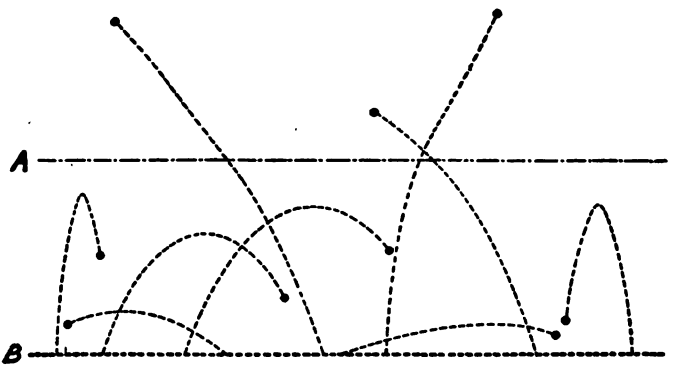


Fig. 9

VAPOR MOLECULES AT THE SURFACE OF A LIQUID

As explained in the text, the vapor which rises from the surface of any liquid consists in molecules which are shot through the film of surface attraction. Slow-moving molecules may penetrate the liquid surface but be returned to it once more by the forces of attraction. Fast-moving molecules, however, may escape permanently. The paths described by molecules of both sorts are illustrated above. *A* is the limit at which the attraction ceases to be effective for a molecule moving sufficiently fast to reach this line. *B* is the liquid surface.

balls will go on indefinitely. Such a room with the balls will represent in a general way a small vessel filled with a gas.[1]

Some of the well-known properties of gases follow in the simplest way from a consideration of the above model of a gas. It is obvious that the walls of the room will be

[1] The analogy here given may appear crude, but an actual model on the general principle outlined, using small steel balls, has been constructed by Professor Northrup of Princeton. When in action, this model exhibits all of the fundamental properties and laws of gases.

bombarded by the flying tennis balls. The walls will, therefore, feel a thrust, that is, they will have an outward *pressure* acting upon them. This corresponds to the well-known pressure of any gas confined in a closed vessel. Moreover, this pressure due to bombardment will be greater if the speed of the flying balls is greater, and hence in the case of a gas we should expect the pressure to increase with the temperature, that is, with the average energy of motion of a molecule. It is a well-known fact that the pressure of a gas does increase in this way (18), (19).

Again, returning to our model, it seems fairly reasonable to suppose (and can, in fact, be proved mathematically) that if the balls in one half of the room have on the average a higher speed than the balls in the other half, there will be a gradual slowing down of the one and a speeding up of the other until all of the balls have the same average speed. This corresponds to the gradual equalization of temperature which goes on in any vessel containing a gas, when at the start one part of the gas is at a higher temperature than another. This transmission of energy in a gas is what is called *heat conduction* (20).

The Brownian Movement and the Visibility of Heat Motion. — If one of the tennis balls above mentioned were much larger and heavier than the rest it would be found to move on the average much more slowly. In the case of a gas, therefore, heavy molecules move on the average more slowly than light ones. As we pass to heavier and heavier molecules or to larger and larger particles of some foreign substance immersed in the gas, the average motion of the particles considered becomes less and less, until it disappears into the imperceptible. Now the question arises whether it might not be possible to detect the motion of particles so large that they could be seen with

a microscope. If this were possible we could obtain a direct view of the heat motion of the gas, for although we should not be able to see the motion of single molecules we could see the closely related motion of a very much larger particle.

Now, as a matter of fact, this continuous random motion of all very small solid particles floating in a gas or a liquid is a well-known phenomenon and is called the *Brownian Movement.* It is so common that biologists have to learn to distinguish between the life-motions of bacteria which they are examining under the microscope and the "*Brownian movements*" which the bacteria have in common with all other small particles.

This Brownian movement is an extraordinary verification of modern ideas of heat for the verification goes farther than was stated above. It has recently been shown that the motion observed under the microscope is not only of the same *kind* but also of the same *magnitude* as that which is predicted mathematically from molecular considerations (21).

A Model of a Liquid. — If we imagine the above mentioned tennis balls to have their average motion slowly diminished, and if we remember that in order to represent molecules the balls must have a slight attraction for each other, it will be clear that finally the balls will no longer fill the room as they did before but will divide themselves into two groups. There will be a layer of balls on the floor adhering more or less closely together, although still vibrating among themselves, and above this layer there will be flying at random the balls which we have already taken to represent a gas. The layer on the floor might be a foot or two thick, depending on the number of balls present, and they would give us the impression of a ceaselessly squirming mass.

This dense layer of agitated balls on the floor represents the surface of the liquid and the flying balls in the remainder of the room represent the gas or vapor which always exists above any liquid confined in a closed vessel.

It will be clear in a general way from this model why "heat expands" in the case of a liquid, for as the violence of vibration increases (and this corresponds to a rise in temperature) the closely adhering balls representing the liquid will, on the average, be forced farther apart and the total volume of balls will appear to fill more space.

In a few rare cases a liquid expands on being cooled. In these cases we must imagine that the molecules are not simple spheres but have more complicated shapes. A change in temperature may therefore result in a different fitting together and unexpected volume changes.

A Model of a Solid. — The model above discussed probably represents the truth in a general way as regards a liquid, a gas, and the relation between the two, but we cannot be so sure in the case of a solid.

The tennis balls, if they are to represent molecules, must not be perfectly spherical. Let us suppose them to be egg-shaped. Let us suppose too that the internal *motion* of the balls on the floor be diminished more and more and that after a while there is a tendency to form orderly arrangements which persist. They will still be vibrating somewhat, but if one of the balls has its sharper end turned in one direction at present, it will be turned in the same direction at a later period. It is as if a net-work of elastic threads fastened the balls together. They are still capable of vibrating to and fro, but any individual maintains permanently a certain position in the total mass.

Such a model probably corresponds to a substance in the solid state, although, as has been said, this is not certain at present. There may be some other subtle difference between a liquid and a solid, but this is perhaps the principal one. One reason why we are not very sure that permanent orderly arrangement is the only difference between a solid and a liquid is because of the existence of orderly arrangement within liquids. *Liquid crystals*, as they are called, are known to exist and certainly are of extreme interest and importance (22).

How Friction Causes Heat. — It will be clear from the above considerations why the rubbing of one surface on another invariably causes heat. The molecules of both bodies are "stirred up" as it were, so that the violence of vibration is increased and this corresponds to a rise in temperature. The energy required to increase the vibration of the molecules comes from the work done in the rubbing.

Why "Evaporation Cools." — That the evaporation of a liquid has a cooling effect is well known to everyone. Boys detect the direction of the wind by noticing the coolness of one side of a wet finger. From the above consideration the reason for this cooling effect is not difficult to imagine. From the surface of a liquid, molecules are constantly passing away to become part of the surrounding vapor. In the course of the random motion which a molecule at the surface of a liquid undergoes it may at certain times, as has been said, attain sufficient speed to enable it to break away from the attraction of its neighbors. (See Figure 9.) Since the deserters will always be molecules which at the moment possess greater speeds than the average, the liquid by evaporation is constantly losing some of its fastest moving particles. Such selective action will result in a gradual decrease in

the average speed of those that remain. This corresponds to a cooling of the liquid (23).

The "Absolute Zero." — It has been said that from the modern point of view the violence of molecular or atomic vibration corresponds to the temperature of a body. Now if we imagine a body to be cooled indefinitely it is clear that sooner or later we should reach a point at which *all vibration* would have ceased, that is, when the molecules and atoms of a body would simply be packed together in an absolutely inert mass. Such a point would correspond to a temperature below which it would be impossible to go, because it is obviously impossible to have less vibration than no vibration.

There are ways (see Section 18) of calculating in terms of degrees Fahrenheit this lowest conceivable temperature although it cannot be completely attained in practice. It is approximately 459° below zero. This temperature is called "the absolute zero" and corresponds to the absence of all heat.

"Heat" and "cold" are consequently not symmetrical terms. "Heat" is molecular motion. "Cold" is the absence of molecular motion, that is, the absence of heat. It is therefore wrong to speak of "adding cold" to a body. We should say, "taking heat away." The value of ice in a refrigerator consists in the fact that it absorbs large quantities of heat from the objects put near it and not that it "gives out cold."

The Heat Energy in Bodies. — From the above considerations it follows that all bodies at room-temperature possess enormous quantities of heat and what we call a "hot body" is distinguished from a "cold body" by the fact that the first has a higher temperature than the *human* body, and that the second has a lower temperature (24).

It may be worth stating that the amount of heat in a glass of water at ordinary temperatures corresponds to an amount of energy which, if utilized mechanically, would be sufficient to raise this water to a distance of thirty miles or more above the ground. Practically the same would be true of a piece of ice, since its *total* heat is only a little less than that of the water.

It may also be worth mentioning that in the last few years temperatures have been reached in the laboratory which are only two or three degrees above the absolute zero. At such low temperatures some of the properties of matter, as we shall see later (Part II, Section 54), undergo remarkable modifications.

CHAPTER V

THE ELECTRON AND ITS BEHAVIOR

We are now ready to consider the second fundamental entity, namely the *electron*. To quote from the first chapter, "according to the modern theory, all bodies are complex structures composed of small particles called atoms and still smaller particles known as electrons."

So far as we know, all electrons are exactly alike. In this respect, therefore, they differ greatly from atoms, which, it will be remembered, exist in about a hundred different varieties.

Size. — In size the electron is very much smaller than the atom. The exact size is not known but it has a diameter of about one one-hundred-thousandth that of an atom. This means that if the average atom be represented by a sphere one hundred yards in diameter, the electron, on the same scale, would be about the size of a pin-head. In other words, a large office building is not

large enough to represent an atom if a pin-head is to represent an electron.

Weight.—The electron is much lighter than any known atom although in proportion to its size it is much heavier. Although the atom is enormously larger than the electron, the lightest atom, namely that of hydrogen, is only about two thousand times as heavy as an electron.[1] A short calculation shows, therefore, that the "density" of the electron is a million million times that of the atom.

The minuteness of the electron may seem almost incredible, but careful research leads almost inevitably to the conclusions stated, and the scientist must report what he finds.

Shape and Structure. — Practically nothing is known as to the shape or structure of the electron. There are indications, however, that it is spherical in shape and symmetrical in every way (25).

The Two Electricities. — It will be remembered by those whose physics is not too distantly lost in the past that there are two "kinds" of electricity, "positive" and "negative." If a body is charged with electricity of one kind it repels all bodies having a similar charge and attracts all those having an opposite charge. In the familiar terms: "like charges repel each other; unlike charges attract each other." The attraction of unlike charges is the common phenomenon noticed when in cold weather a recently used comb is held near bits of paper. *At present it seems not improbable that most of the phenomena in nature are due, in the last analysis, to electric attractions and repulsions* (26).

[1] Strictly speaking it is the "mass" and not the weight that we refer to, but the term "weight" is in common use and of proper implication.

Both Kinds of Electricity Abundant in all Bodies. — All bodies seem to possess enormous quantities of both positive and negative electricity, but usually it is in exactly equal amounts, so that one kind neutralizes completely the effect of the other and no electricity seems to be present. Charging a body with electricity is then to be considered as merely disturbing this balance by taking away or adding to the body a small amount of one kind of electricity. We shall see later that the electricity added or taken away appears in the light of modern theory always to be the negative.

Electrons Negatively Charged. — Each electron has a negative charge of electricity and this charge, considering the size of the particle, is very great. Electrons are therefore, attracted towards all positive charges of electricity and at the same time repel *each other* strongly. Modern research has made it probable that not only do electrons *always* possess a negative charge but *negative electricity exists only in the form of electrons.* That is, negative electricity and electrons are inseparable and the only way to give a body a negative charge is to put electrons on it or in it.

Atoms and Electricity. — Since all bodies are made up of atoms, charging a body with electricity is the same as charging some of its atoms with electricity. Speaking now of "atoms" instead of "bodies," it follows from the above that no *atom* can be charged with negative electricity without putting one or more electrons on it. Each ordinary atom contains a number of electrons and enough positive electricity to exactly balance the negative electricity of the electrons. At present it appears that *the positive electricity never leaves the atom,* whereas electrons allow themselves to be taken away from or added to the atom with relative ease.

Negative Charge "Too Many" Electrons; Positive Charge "Too Few." — Since it is probable that only negative electricity in the form of electrons is movable, an atom can be charged positively only by taking away some of the electrons which it normally possesses. This allows the positive charge of the atom (which it has perpetually) to predominate and produces the same effect as if positive electricity had been *added* to it. Thus briefly, an atom contains normally a certain number of electrons and also positive electricity enough to neutralize exactly their negative charges. The atom is then "uncharged." If an electron is added to the atom from the outside there will be more negative electricity than positive and the atom will have a "negative charge" (27).

The Electric Current. — The attraction which an atom has for an electron varies greatly with the different species of atoms. The atoms of the so-called metals exert only a relatively weak attraction on electrons, whereas the attraction of the "non metals" appears to be greater. In a metal, therefore, it will be relatively easy to move electrons from place to place.

When a stream of electrons is caused to move through the body of such a substance we have an electric current. From the modern point of view, therefore, an electric current in a wire is a stream of electrons moving through the relatively large spaces between the atoms or through the atoms themselves (28).

The electrons forming the electric current move very slowly, perhaps only several inches a minute, but they move in enormous numbers. This speed must not be confused with the so-called "speed of electricity." The far greater "speed of electricity" is due to the fact that the *impulse* is passed on very rapidly from electron to electron, so that when the electrons at the near end of

a hundred mile wire are set moving those at the distant end are caused to take up the motion a very small fraction of a second later. Briefly, the actual speed of the electrons is very slow, but the rate of transmission of motion from electron to electron is very great. The action is closely similar to what follows when one end of a long rope is pulled. The impulse which results in the movement of the other end travels with much greater speed than the rope itself commonly attains.

In the electrical case, the impulse to move travels with the speed of light, *i.e.*, one hundred and eighty-six thousand miles a second, whereas the electrons themselves (*i.e.*, the true electricity) move only a small fraction of an inch a minute.

The Action of a Battery or Dynamo. — Since it appears probable that electricity in its movable state always consists of one or more electrons, it is clear that no machine or device of any kind can *produce* electricity (29). What it does is to *drive* electricity. Hence a battery might be called "an electricity pump" or perhaps even "an electron pump." Because of the chemical action taking place within the battery it is enabled to force electrons out through its negative terminal, and these electrons flow through the wires of the outside circuit and re-enter the battery again through the positive terminal.

We pay a lighting company, therefore, not for "electricity" but for electrical energy. Nor is electricity "used up" when the current passes through the filament of an incandescent lamp. Precisely as many electrons leave the filament as enter it, but the stream as it passes through tends to set the atoms in more violent vibration, and so heats or maintains the temperature of the filament.

The electric transmission of power is thus closely

analogous to the transmission of power by compressed air. We must stipulate, to improve the analogy, that the compressed air when "used" at the far end of the pipe-line be not set free, but returned by another pipe to the air compressor. Under these conditions, if the action goes on for a long enough time, the same air will go several times around the circuit. Air is not consumed, nor is it manufactured. It is simply compressed, that is, pumped around the circuit. The "consumer" who pays for compressed air under these circumstances gets value because the air comes to him at a high pressure and he sends it back at a low pressure. He has consumed energy and not air.

The difference in air pressure in the pipes corresponds to the "voltage" of an electric transmission line (30).

"*Free Electrons.*" — It has been said that the atoms of different elements seem to have different attractions for electrons. Recent experiments have made it probable that the so-called "positive" elements, including the metals, have a relatively weak attraction and the negative elements, such as sulphur, a powerful one. Many electrical phenomena probably owe their existence to this fact.

It is doubtless owing to this difference, for example, that metals conduct electricity so readily, whereas substances like sulphur do not. We must suppose that the atoms of a metal have such a weak attraction for electrons that a vast number of the latter are in a practically free state throughout the body of the metal and are thus capable of being moved readily by any outside electric forces. This ease of movement makes the substance a good conductor. Atoms of such elements as sulphur, on the other hand, possess such great attraction for electrons that most of them are held tight in the atoms and

cannot be moved easily from one place to another within the substance. This makes the material a "poor conductor," or, as we say, a "good insulator."

There is good reason for believing that the electrons within a conductor act as regards heat motion as if they were small atoms, that is, they take part with the atoms or molecules in the random vibration which appears to constitute the heat of a body.

The "Evaporation" of Electrons. — If electrons exist in large numbers within the substance of a metal it might be expected that if a metal were heated hot enough some of these would be given off into the surrounding space, after the manner in which a liquid loses molecules by evaporation. In fact this is found by experiment to be the case. The emission of electrons appears to be in every way analogous to the evaporation of a liquid (31).

CHAPTER VI

ELECTRONS, CHEMICAL ACTION, AND LIGHT

Electrons and Chemical Action. — It seems probable that the forces involved in chemical affinity are electrical in character, that is, the atoms which form the groups known as molecules are held together by electric attraction. Thus a molecule of hydrochloric acid is composed of one atom of hydrogen and one atom of chlorine, and the two cling together, probably because the chlorine atom has a negative charge, while the hydrogen atom has a positive one, and "unlike charges attract each other."

When hydrogen gas and chlorine gas are put together in a vessel, heat and even light will cause them to combine suddenly and to form hydrochloric acid. That is, each atom of one kind becomes attached to one of the other

kind, forming a molecule of the new "compound," hydrochloric acid.

We are on rather treacherous ground at this point, but we shall probably be not far wrong if we picture the mechanism of the process of union somewhat as follows. The light or heat detaches from some of the atoms a few electrons and these bound about at random between the molecules of the two separate gases. A very important fact then makes itself felt. As was said in the last chapter, different kinds of atoms have very different attractions for electrons, and, in the present case, the attraction of the chlorine atoms is vastly greater than that of the hydrogen. Thus it will happen before long, since a few new electrons are being detached constantly, that every chlorine atom has one electron *too many* while every hydrogen atom has one electron *too few*. This means, of course, that each of the former attains a negative charge, and each of the latter a positive one. The remainder of the process consists in the attraction, and permanent combination in twos, of these atoms of unlike charge to form the groups which we call hydrochloric acid molecules (32), (33), (34).

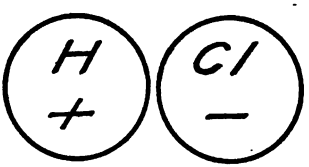


Fig. 10

THE CONSTITUTION OF A SIMPLE MOLECULE

The molecule which is symbolically represented above is one of hydrochloric (muriatic) acid. As shown, it is made up of one atom of hydrogen, *H*, combined with one atom of chlorine, *Cl*. The former bears a positive electrical charge, and the latter an equal negative charge. It is the attraction between these opposite charges which is supposed to hold the molecule together. When the charged atoms are separated, as in "electrolytic dissociation" (see text), they form hydrogen and chlorine "ions."

This theory of chemical action is not certain as yet but is worth mentioning.

It is to be noticed that some kind of disturbance, in the above case heat or light, is necessary to keep up the

supply of "free electrons." We see, therefore, that were there no heat or light, or were the intensity of these below a certain limit, depending on the nature of the substances, we could get no chemical action (35). This inertness would probably be a property of *all* substances in the dark at the so-called absolute zero of temperature (36).

Atoms, Electrons and Light. — There is good reason for believing that light-waves are electrical in character. There seems to be no fundamental difference between light-waves and the electric waves used in wireless telegraphy, except that the latter are very much "longer" and the vibration is very much slower than in the former case. Light-waves and "wireless" waves are thus related in the same way that a high-pitched sound is related to one of low pitch.

"Wireless" waves (*i.e.*, "Hertz" waves) are always produced by causing a charge of electricity to oscillate to and fro. According to the prevailing view, waves are thus set up in the "ether of space" in a manner somewhat similar to the way sound-waves are set up by a vibrating bell (37).

Since an oscillating charge is thus the cause of these waves it seems reasonable to ask what electric charge is responsible for the closely similar but vastly more rapid waves of light. This question has been asked, and answered by studying the effect of a powerful magnet on various sources of the vibrating charges within the glowing body which must be held responsible for the light-waves emitted. Results obtained by a distinguished Dutch scientist lead to the conclusion that *the charge is that of the electron.* Here again, therefore, we are thrown back on the same fundamental entity (38).

The "radiant heat" from the sun is also of this electric-

wave type of vibration so that the sun must be considered a light and heat radiator because of the vast number of vibrating electrons which it contains.

To sum up: *according to the modern wave theory, whenever an electric charge, whether this charge be that of one electron or many, vibrates back and forth, it radiates electrical waves which go out in all directions in space* (39). If the oscillation is very slow they are called Hertzian waves, or "wireless" waves. If the oscillation is more rapid they are in general termed "heat-waves," and if the vibration is still more rapid the waves are capable of affecting the retina of the eye, and are called "light-waves" (40).

All of these waves can be absorbed, refracted and reflected. They all transmit energy and hence are capable of heating any body which absorbs them.

The Absorption of Electric Waves. — The mechanism of the absorption of electric undulations is to be thought of as follows. As a sound-wave which is emitted from a vibrating body tends to set any body which it strikes into a similar vibration, so an electric wave which is emitted by an oscillating electric charge tends to set vibrating the electric charges within the body which it strikes. If these charges are so conditioned that they are capable of responding easily to the particular rapidity of vibration which thus strikes them, they will be set into violent vibration at the expense of the energy of the entering wave. This vibration ultimately becomes the random motion of heat.

Since absorption is apparently due to motion of the electrons which a body contains, it follows that opaqueness in bodies must be ascribed to this electron mobility. It is probable that if the electric charges within a body could be held fixed, the latter would be transparent to any electric wave.

The Reflection of Electric Waves. — When the electrons within a body are set into vibration by an impinging light-wave they will, of course, act as radiators of new light-waves, and if the body has a flat surface those emitted from the electrons near the surface will join to form a definite single wave which travels back in an opposite direction to that of the entering one. This constitutes the reflected wave, which exists in general whenever light strikes a flat surface. The reflected wave may be almost as strong as that entering or it may be very weak, but except in ideal cases it always exists.

Whether the surface is flat or not there will always be reflection, but if the surface has a certain degree of flatness the reflection will not be "diffuse" like that from a white-washed wall, but will be regular, like that from a mirror (41).

The Speed of Electric Waves in Different Bodies. — It is a generally accepted fact that all electric waves whether they correspond to light, heat or Hertzian waves, travel with the *same* speed in empty space, but with different speeds in material bodies. The explanation of this is that all material bodies contain electrical charges and that the wave which passes through the body is a complex resultant of the original entering wave and the secondary waves which are set up when the charges oscillate in response to the entering wave. This complex resulting wave, although it has the same vibration frequency as the original one, is altogether differently conditioned and it can be shown mathematically that it will not travel with the same speed (42).

CHAPTER VII

ELECTRONS AND MAGNETISM

The Connection of Electricity with Magnetism. — It is a well-known fact that magnetism always exists in the region surrounding a wire carrying an electric current. Since the trend of modern theory is towards the conclusion that an electric current always consists in the bodily movement of electrons or atoms, we must suppose magnetism to accompany invariably the motion of electric charges, and indeed this has been found to be true (43).

Any magnetic effect can best be magnified by winding the wire which is to carry the electric current around a piece of iron in the same general way that thread is wound upon a spool. The wire must, of course, be insulated so that the various turns do not touch each other. Such an iron spool may become a strong magnet when a current of electricity is sent through the wire surrounding it. This is the principle at the basis of the action of the ordinary electric motor. The electric car is kept moving because the current which enters through the trolley wire, and leaves through the track, passes through a wire wound on a similar spool, and the spool (then a magnet) through its attraction sets rotating other pieces of iron which are attached to the wheels of the car.

Deflection of Electrons Caused by Magnetism. — It can be shown that if an electric charge is caused to move rapidly past the end of a magnet, the charge tends to be deflected sidewise. This lateral deflection of electrons in a so-called "magnetic field" corresponds to one of the fundamental relations between electricity and magnetism,

and by its means we have an important method of "generating" an electric current, *i.e.*, of moving electrons. Suppose for instance that a piece of wire is moved rapidly through a magnetic field, that is, near a magnet. The piece of wire in common with all conductors contains countless easily moved electrons, and when the wire is moved through the field the deflecting force mentioned above causes them to be pushed towards one end of the wire, if the latter is held in the proper position (44).

The Action of a Dynamo. — The ordinary dynamo or electric generator, as it is often called, is a machine for moving wires rapidly through a magnetic field, and for collecting the electric current which is set up by the deflecting forces above mentioned. Such a machine has, of course, to be run by some outside source of power such as a steam-engine, or a water-wheel.

Permanent Magnetism. — The familiar type of magnet which is not maintained by means of an electric current, the small red-painted horse-shoe magnet of the toy-shops, for example, is called technically a "permanent magnet."

It is probable that the ultimate cause of magnetism in this case is quite similar to that in the case of the spool before mentioned. In the latter, electrons circulate in a helix around the outside of a large piece of metal, and in the former, although there is no circulation of electrons around any visible path, helical or circular, still such paths probably exist within the molecules of the iron which forms the permanent magnet. According to the present belief, the electrons within a piece of magnetized iron do not move in a wholly random fashion, but have what we might call a "helical prejudice," and perhaps even revolve in circles within the molecules themselves.

It is now generally believed that the cause of magnetism is always the motion of electrical charges (45).

The Effect of Magnetism on Light. — Since the source of the light which an incandescent body emits lies in the vibratory motions of electrons within the body, and since magnetism has a tendency to deflect moving electrons, we should not be surprised to find that certain sources of light when put near a powerful magnet have their emitted light modified in a complicated way. This has been found to be the case, and the results tend to verify the views herein set forth (38).

CHAPTER VIII

RADIO-ACTIVITY

There is a remarkable group of substances which emit rays continuously, without obtaining energy from their surroundings. Radium is, perhaps, the most striking member of this group and it is now known with considerable surety that in its case the rays would only fall off to about half their present intensity in two thousand years. This extraordinary action goes under the general name of "radio-activity" and the substances which emit the rays are known as "radio-active substances" (46).

The Three Rays. — The rays emitted are not all of the same kind, but are composed of three distinct types, each with definite characteristics of its own. It was thought convenient in the beginning to designate these rays by the first three of the Greek letters, and they are therefore known as the *alpha rays*, the *beta rays*, and the *gamma rays*.

The Beta Rays. — There is now no reasonable doubt that the beta rays consist of a stream of electrons coming out of the substance like bullets from a machine gun. The most surprising thing about these rays is the enor-

mous velocity of the electrons. Their speed is almost equal to that of light, or about one hundred and eighty-six thousand miles a second. This inconceivable velocity is measured indirectly, but by methods which make it almost certain that the result is correct. This speed enables part of the rays to penetrate a plate of metal as thick as an ordinary book cover (47).

The Alpha Rays. — Within the last few years it has become practically certain that these rays consist of a stream of *atoms of the element helium.* This surprising fact could certainly not have been predicted when first the rays were discovered. The helium atoms have each a double positive charge; each atom, that is, has lost two electrons. The atoms of the stream have a velocity of about one-tenth that of light, or about eighteen thousand miles per second. This is less than the speed of the beta rays, but it must be remembered that the atom of helium, whose "atomic weight" is four, is about eight thousand times as heavy as an electron, and thus, although the helium atoms of the alpha rays are moving more slowly, their energy is much greater than that of the beta ray particles, the electrons (48).

This energy is in fact so great that a single "alpha particle," that is, a single atom of helium, when it strikes certain substances, will cause them to phosphoresce (or more properly fluoresce) for an instant over a region large enough to be seen with a lens. This makes visible the effect due to a single atom and gives us *the first case in the history of science where any effect caused by one atom has been observed.*

The Gamma Rays. — There has been some dispute as to the ultimate nature of the gamma rays, but it is now practically certain that they do not consist of particles in the ordinary sense, but of impulses similar to those con-

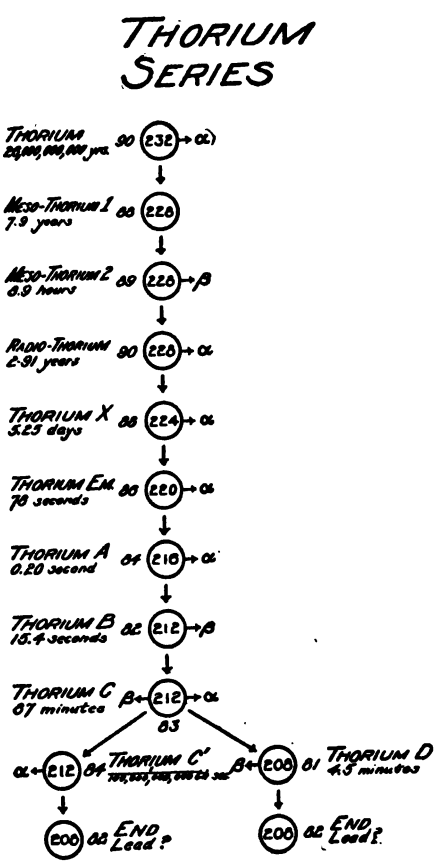


Fig. 11a

THE RADIO-ACTIVE ELEMENTS AND THEIR RELATIONSHIPS AND RAYS

These diagrams represent symbolically the four series of radio-active substances. In each vertical line the elements above break down to produce those immediately below, as indicated by the arrows. During this decomposition they emit the types of radiation designated by the Greek characters attached to the horizontal arrows. Some of the substances, such as Meso-Thorium 1 and Actinium, are rayless. The periods of time indicated beside each element stand for the intervals required in order that half of a given quantity of the element in question should have decomposed. Thus, if we set aside a gram of Radium to-day it will amount to only half a gram when two thousand years have elapsed. The other half will have gone through the change symbolized in the diagram. The figures inside the circles are the respective atomic weights; those outside, the atomic numbers.

URANIUM SERIES

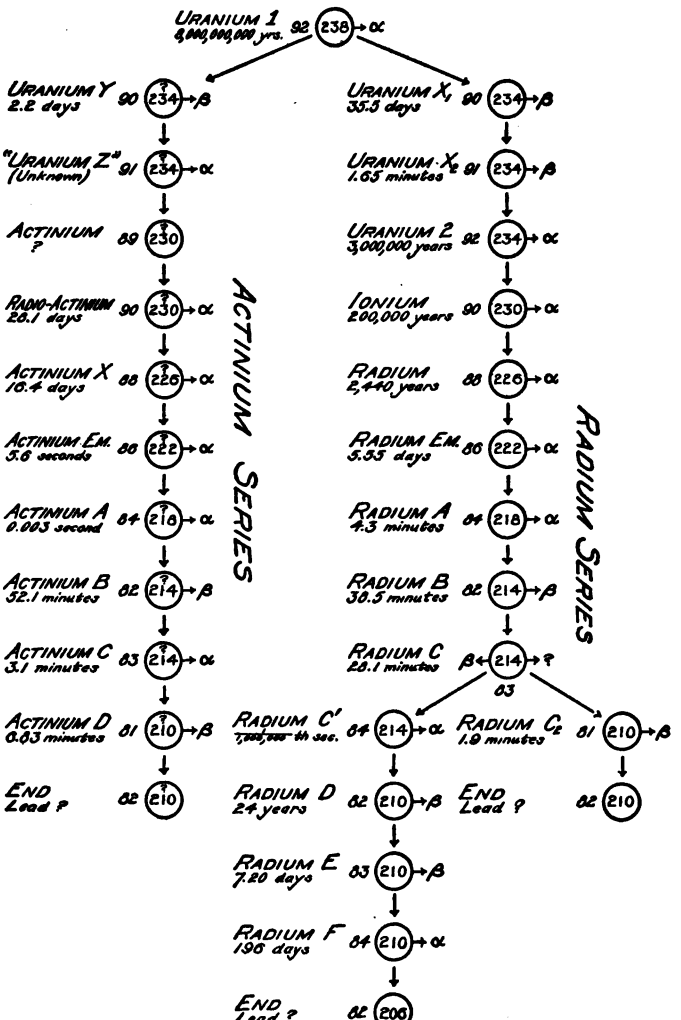


Fig. 11b

stituting the X Rays and not very dissimilar to the waves or impulses making up light.

The connection between the beta rays and the gamma rays is probably similar to that between the bullet and the sound in the case of a gun. Both the bullet and the sound of the explosion travel away from the mouth of the gun, but the bullet is *a moving object* while the sound is a disturbance, or a wave impulse in the air. In perhaps the same general way both the beta rays and the gamma rays come out of the radio-active substance, but the beta particle is a moving electron while the gamma rays are probably electric wave impulses. Both rays, however, like the bullet and sound, leave the source together (49).

Cause of Radio-Activity. — It is now generally believed that the cause of radio-activity is the actual breaking up of the atoms of the radiating substance. The radium atom "explodes," like a bomb, into two "pieces" and the energy of the explosion gives each "piece" a high velocity. The two pieces are a helium atom and an atom of an element previously unknown. The new element is called "niton" or "radium emanation" and appears to be a heavy gas belonging to the same group in the periodic system of elements as do helium and argon.

We have then, in radio-activity, a case of natural alchemy, but since it has been found impossible, so far, to hasten or retard the process artificially, the knowledge of radio-activity would not have helped the alchemists in their quest.

Successive Disruptions of Radio-Active Atoms. — The radium atom appears, in fact, to be a member of a *chain* of "explosive atoms" for the atom of "niton" itself is radio-active. If given time, it will itself "explode" and give off another helium atom. The chain has been fol-

lowed out through nearly a dozen elements, as shown in Figure 11.

Radio-Activity Not a Chemical Change. — It must be borne in mind that the change accompanying the process of radio-activity is *not a chemical change.* As has already been stated, a chemical change involves the *regrouping* of the atoms to form new molecules. This does not affect the integrity of the individual atoms but only their relations to their neighbors. In radio-activity, on the other hand, we have changes which involve *the actual disruption of the atom.*

Intra-Atomic Energy. — When coal is burned, the energy is derived from the attraction existing between the atoms of carbon (coal) and the oxygen atoms of the air, and it should be evident that in general whenever there are strong attractions or repulsions between different atoms, there is a possibility of obtaining energy by allowing these forces to act. The energy developed in radio-activity has also its origin in forces acting within the substance, but they are not the forces acting *between* the atoms, as is the case with all chemical energy, but those acting *within* the atom, the so-called "intra-atomic forces."

We may therefore say with truth that all the energy obtained in the world from fuel is of the *extra-atomic* variety, while the energy of radio-activity is something quite new. It comes *out* of the atom and is therefore *intra-atomic* energy.

The Quantity of Intra-Atomic Energy. — One of the most remarkable facts about these *intra-atomic* forces is their great size compared with the *extra*-atomic forces of chemical action. The slowness of the radio-active changes tends to conceal this but it is nevertheless true.

The energy given off by radium ultimately becomes

heat and this heat has been directly measured a number of times. Since the radium would be half gone in two thousand years, a simple calculation shows that the *total energy given up by radium and its products during transformation is about a quarter of a million times the energy to be obtained by burning an equal weight of coal.* To make this statement a little more vivid, the fact might be noted as an illustration that a large ocean steamship could make one ocean passage on the energy from a few *pounds* of radium and its products (50).

The Radio-Active Elements. — There appears to be nothing unusual about the radio-active elements except their radio-activity. For example, referring to Figure 11, radium itself belongs to the same chemical family as barium and behaves chemically like barium. The next element, the atoms of which are formed from the disruption of the radium atom is the gas called "niton" (radium emanation) already mentioned. The following one, "radium A," so called, is a solid substance.

The atomic weight of radium is about 226, that of niton about 222 and that of "radium A" about 218. These numbers correspond with the fact that the alpha particle (the helium atom) which comes off at each explosion has an atomic weight of 4, so that each of the above elements has a weight of 4 less than the element from which it sprung.

Are All of the Elements Radio-Active? — There is some reason to believe, although as yet no proof, that all elements are decomposing in the same way, or in other words, that radio-activity is a universal property of matter. This means, of course, that in the case of the well-known "permanent" elements the process is so slow as not to be noticeable. Already potassium has shown signs of being radio-active and as methods of measurement be-

come gradually more delicate it is not improbable that other elements will do the same (51).

The Evolution of the Elements. — The probability that all elements are to some degree radio-active has led to the general conception of what is called the "evolution of the elements." According to this view there is a slow forming of the lighter elements through the disintegration of the heavier ones. The well-known elements are to be considered as merely those whose average "life" is so great as to make them, from a human point of view, permanent. If this conception be a true one, if the atoms of any element are descendants, as it were, of the atoms of heavier elements, then it is not difficult to understand in a general way why the well-known relations of the periodic system exist between the elements.

One objection which has been raised to this view is that, did such evolution exist, it must have completed itself years ago and hence only the lighter elements should now remain. There are, however, some faint indications that under conditions differing greatly from those on the earth, such namely as exist in the hotter stars, the reverse process may be going on. This would involve the building up of the heavier elements out of the lighter ones. At present, however, such a suggestion is mere speculation (52).

CHAPTER IX

THE STRUCTURE OF THE ATOM

The study of radio-activity opened the door to the knowledge of intra-atomic phenomena and recently it has given us some *definite* ideas as to the details of atomic structure.

General Principles. — One or two general statements must be made at the outset. In the first place, electricity certainly plays a highly important rôle in the formation of the atom and the intra-atomic forces must be largely electrical. Whether *all* intra-atomic force is of this nature is a question which cannot be answered at present.

Secondly, we can say without much chance of ultimate contradiction that the atom is very much more "porous," or "open work," in structure than the appearance of the vast aggregates of atoms which we know as "bodies," would lead us to believe. It has been stated that some of the beta particles (electrons) from radium, travelling with nearly the velocity of light, go straight through a piece of metal as thick as the average book cover, and it needs but a very short calculation to show that this means that the electron penetrates more than a million atoms one after the other. It must be remembered that in a solid substance the atoms are quite near together so that such a flying electron has no chance of travelling entirely in the space between the atoms during its whole passage through the metal.

If the atom is made up almost entirely of electrons, it is easy to show that, on the average, the electrons must be as far apart compared with their size as are the planets in the solar system. This at first sight seems incredible, but it is not more so than many of the accepted facts of astronomy.

The Evidence for Orderly Structure in the Atom; Spectral Lines. — Although much of the light and heat given out by bodies seems to be due to the *random* vibration of the electrons within them, this is by no means invariably the case. Almost all *gases* when caused to give out light, emit it in the form of "pure notes," that is in the form of waves of definite frequency. The light which we get from a

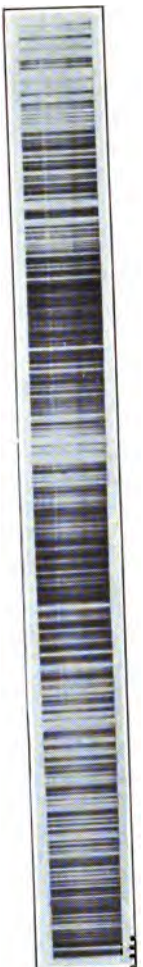
Part I

Men of Spectrum and Mind

Plate I

LINE SPECTRUM OF IRON

This plate shows two, partly overlapping, portions of the line spectrum of iron. The photograph was taken with a spectrograph provided with lenses and prisms made of quartz, and hence shows the ultra-violet lines very clearly. The source of the light was a so-called "iron arc," produced by the passage of an electric current between two slightly separated iron points, in air. It is the vaporized iron in the arc which gives rise to the line spectrum.



white-hot nail consists of all possible frequencies of vibration. It is similar to what we should obtain in sound if we took a long rod of wood and struck *all* the keys of a piano at once. The light, however, which we get from a glowing *gas*, such light as comes from the long glass tubes now frequently used in garages and known as Cooper Hewitt Lamps, is not of this chaotic composition. It can be shown to consist of "a few pure notes," to use the same acoustical analogy. These pure "notes," or colors, are superimposed upon each other and hence the combination is a close analogy to what we call in acoustics a musical chord.

The definite "light notes" emitted by one substance when in the gaseous form are perfectly characteristic of that particular species of atom and *no other kind of atom gives off the same notes;* no other kind of atom, that is, emits light of just the same frequencies.

This can only mean that the electrons within, or about, one kind of atom are in some definite arrangement or move in some definite way and one which differs markedly from that to be found in atoms of other species (53).

CHAPTER X

RECENT DISCOVERIES CONCERNING ATOMIC STRUCTURE AND RADIATION

The last five years have brought marked developments in fundamental physical theory.

Of the three fundamental entities, atom, electron and radiant energy, the electron alone has remained to our view about where it was a half decade ago, but our conceptions of the atom and of radiant energy have changed considerably.

Recent Advances Concerning the Atom. — New light on the structure of the atom has come largely through the study of radio-active substances. From researches of Rutherford and his associates, it now seems highly probable that the atom is made up of a minute, positively charged nucleus surrounded by several rings or, better, *regions* of electrons. The total number of electrons is such that their total negative charge is equal to the positive charge on the nucleus.

Since the volume of the nucleus and the volume of the electrons is in all cases very small compared with the dimensions of the system, the major part of the volume of an atom is unoccupied in the ordinary sense of the word. This space is "empty" in the same sense that the space around a large charged body is empty, and the law of electric attraction and repulsion within the atom appears to be the same as for large charges; namely: the well-known "inverse square law."

What are at present believed to be the facts regarding atomic structure are, perhaps, somewhat intricate, and clearness can best be attained by making a formal list.

1. The atom consists of nucleus and surrounding electrons.
2. The electrons are negatively charged; the nucleus positively charged.
3. Both electrons and nucleus are very small compared to the distances between them.
4. The nucleus is composed of a certain amount of negative electricity and a *larger* total amount of positive electricity.
5. The nucleus may lose either negative or positive electricity, but it always does so in definite units, the negative unit being the electron and the positive unit equal to two electrons. *Such losses occur only during radio-activity.*[1]
6. The law of electric attraction between the nucleus and electrons in the surrounding space is the familiar "inverse square law."

[1] Nothing is known as yet regarding actions or relations inside the nucleus.

7. The surrounding electrons have a total charge equal to the positive charge on the nucleus, so that an atom in the ordinary state has no resultant charge.

8. The electrons surrounding the nucleus exist in two or more rings or regions at markedly different distances from the nucleus.

9. The more distant electrons are those chiefly concerned in chemical action.

10. The chemical properties of an element are determined chiefly or entirely by the number of electrons surrounding the nucleus and hence by the charge on the nucleus. (See 7 above.)

11. If, therefore, a nucleus loses *two* negative units (electrons) and *one* positive unit (see 5) the atom which results will not be distinguishable *chemically* from the original one.

12. The above action will, however, result in a loss of weight and the new atom will, therefore, have a less atomic weight than the original, although chemists will have given the two elements the same name.[1]

13. The electrons surrounding the nucleus are probably in motion about it.

14. Violent physical phenomena may temporarily remove electrons from the atom (but not from the nucleus) and, in chemical combination, one atom may have some of the electrons belonging to another.

15. During the change in grouping or during the removal of electrons from the region surrounding the nucleus, electric waves (light, X Rays) are radiated.

16. Changes in the *nucleus* only occur during the process of radio-activity and cannot therefore in any way be caused to happen artificially.

17. The "beta rays" are electrons escaping from the nucleus and the "alpha rays" are positive units escaping from it.

18. The "gamma rays" are the electric wave radiations resulting when electrons are violently ejected from the nucleus during radio-activity.

19. There is some mysterious action at work which prevents the surrounding electrons from falling into the nucleus. This action is probably closely related with the existence of the "Quanta" of Planck (*vide infra*).

[1] Two such chemically identical elements with different atomic weights are now called "isotopes."

Atomic Numbers. — Since the chemical properties of an atom seem to be determined principally, if not entirely, by the resultant charge of the nucleus, it is this charge which fixes the place of the atom in the "Periodic Table," so familiar to chemists (see Section 6). A series of numbers have therefore been defined, and called the "atomic numbers," which appear to be more vital to the chemist than the atomic weight. The reason for this, as mentioned before (see 11 and 12, above), is that the weight of the nucleus depends on its internal make-up, while its action on the surrounding electrons depends only on its resultant charge, that is, only on the excess of positive over negative electricity present. Weight is not an interesting chemical feature; resultant charge (measured by the atomic number) is.

The "Quantum" Theory. — A decade ago an epoch-making paper was published by Max Planck, Professor of Physics in the University of Berlin. The revolutionary feature in Planck's work was the suggestion that the atoms of matter did not radiate energy continuously, but in small definite units. In the more radical forms of the theory, as developed by other investigators, radiant energy, such as energy from the sun, is considered to be in the form of separate units in space: "bullets of energy," one might say. This means that the light and heat from the sun fall on the earth like a shower of rain. Planck called the separate units "Light Quantities." [1]

This conception of radiation is in marked contrast to the classical wave-motion theory which unquestionably represents a vast host of facts almost ideally. According to the wave-motion view, a disturbed electron radiates a continuous wave in all directions like a stone dropped in a pond. If the electron made a regular series of vibra-

[1] "Licht Quanta."

tions, a train of such waves would spread out in concentric spheres and we should have continuous light radiation.

In Planck's theory, however, it is more as if the electron emitted bullets of radiation. Just how this occurs he does not attempt to say.

Of course a mere baseless suggestion is worth nothing in physics and Planck would not have hinted at such a heterodox notion had he not found that a hitherto stubborn paradox in the theory of radiation was apparently removed by it.

It will be remembered that all bodies by virtue of their temperature send out radiant energy. In general the higher the temperature the more total energy is radiated in a second and also the higher is the average frequency (39) of the radiation. In the case of light this is equivalent to saying that the higher the temperature the *brighter* and the *bluer* is the emitted light.

Now with certain limitations the amount of this radiation had been found by experiment, but up to the time of Planck's work no one had been able to give a satisfactory theoretical explanation of the results. The two most notable attempts at explanation were those of Rayleigh and Wien. Each of these covered satisfactorily part of the facts but neither covered all. Planck found that by using the new hypothesis he could not only give an explanation of the experimental results, but his mathematical formula contained within it both the Rayleigh and the Wien formulæ.

It was this success which gave Planck the courage to make such an extremely heterodox suggestion as that of light radiation in units.

Although meeting with this initial success it has only been within the last few years that Planck's view has, in the minds of those most competent to judge, passed from

a possibility to a probability. This has been due not only to further study of the direct problem of radiation, but to indirect evidence received from other fields of physics. Perhaps the most important confirmation of the new view has come from a study of the action of light on metals. Certain experiments along this line, notably those of Professor Millikan of the University of Chicago, give results which in the opinion of some are almost conclusive evidence for the existence of "Quanta."

Less direct, but also pointing in the same direction are the results of recent very low temperature research.

The "Quantum Hypothesis" has certainly become a very impressive one, to say the least. Just how impressive, will of course depend in part on the temperament and *a priori* ideas of the investigator.

As to *a priori* probability it should be noticed that at one time matter and electricity were both pictured as continuous but that further knowledge showed that they were both atomic. It does not seem very strange that the third member of the trio of physical fundamentals, namely radiant energy, should also turn out to be "atomic."

The real difficulty before the Quantum Hypothesis is the necessity of joining hands with the classical electrical theory. There can at present be no reasonable doubt that the oscillation of large charges, as in wireless telegraphy, sends out long waves in the manner required by classical theory. Observation and experiment are unanimous in their approval of the well-known electrical laws. It is only when we get to the minute charges in a single atom that new laws seem to make their appearance.

Perhaps the most important question which the theory of radiation presents to-day is therefore the following. How is it possible for big slow phenomena to follow

one set of laws and for small quick phenomena which are unquestionably of the same general nature, to follow another set?

The answer to this cannot now be given, but it seems probable that the answer when it comes will in some way show that one set of laws corresponds to the "averaging out" of the other set. The way in which an army moves, as seen from a high balloon, is quite different from the way a single man moves, and yet it is made up of men. The army moves continuously, but a single man moves jerkily in steps.

The Quantum Hypothesis is at the very center of discussion and controversy in present-day physics.

The Similarity of All Forms of Radiant Energy; X Rays. — Until very recently it had never been found possible to reflect X rays in the way in which light is so easily reflected from a mirror.

It had been suggested by several investigators that this was probably due to the fact that X rays were waves of such extremely short length that the flattest surface that could be made was too rough to reflect them. If any surface, even a polished one, be examined with a high-power microscope, it will be found to be rough and irregular in detail, and the idea was that such a surface, although flat for light waves, might be like a ploughed field for the extremely more minute X rays.

The obtaining of a theoretically "smooth" surface for X rays appeared hopeless, therefore, until Laue suggested in 1910 that natural crystals, if carefully broken, should present a surface smooth and flat beyond anything artificially possible. This would be due to the fact that, in a freshly broken crystal surface, the molecules would be arranged regularly, like the bricks in a pavement.

As a matter of fact, when a crystal of mica was so broken and tested, beautiful X ray reflection resulted. This simple, but epoch-making experiment, served as the starting point of a long series of experiments by various investigators which have resulted in practically proving that X rays are precisely similar to light, but have a shorter wave-length.

Just as X rays may now be looked upon as light waves of extremely short wave-length, so the gamma rays which come from radio-active substances may be regarded as X rays of exceedingly short wave-length. At the present time, therefore, it is very probable that all forms of radiation, from Hertz waves through "heat," light, ultra-violet light, and X rays, to gamma rays are essentially similar in form, though how they can at once show wave characteristics and the bullet characteristics of the Quantum view is still a puzzle.

CHAPTER XI

ATOMS AND LIFE

To avoid possible objections to the general validity of the modern theory of matter it may be well to point out the relation of atomic ideas to the physical structure of living things. Biologists say that all living things are composed of cells, minute objects which are visible in the microscope and have a definite structure. Typically, their shape is not very distant from that of a sphere, and the so-called "cell-wall," like the skin of an orange, simply surrounds the whole. These cells, they say, are singularly independent, sometimes even capable of living alone, in which case the single cell is called a "one-celled animal" (or plant).

From a modern point of view the cell is thus the "vital unit" of all living things. It performs for itself all the life functions which the vast aggregates of cells which we know as animals or plants also do.

Now it is clear that if we are to consider *all* matter to have atomic structure, living substance as well as "dead," the atom must be very small indeed compared with the cell, for otherwise there would be too few possibilities of structure to account for the wonderful complexity of cell action. A rich mosaic cannot be made from a small number of pieces.

The complexity of cell action and that of living things in general does not, however, in any way contradict the ideas of atomic structure here outlined, for the reason that most cells are so large as to be seen clearly with the microscope. Thus the smallest cell so far studied with the microscope certainly contains several million atoms at least, and hence the "mosaic possibilities" are almost unlimited.

From a fundamental point of view we must look upon the physical side of the changes known as life processes as consisting in the continual rearrangement, grouping and regrouping, of the molecules themselves or of the atoms making up the molecules. With so many atoms composing the physical substance of a single cell the possibilities of change are vast (55).

END OF PART ONE

PART II

Section 1

THE SOURCES OF THE MODERN THEORY OF MATTER

The foundation of the "new physics" lies in the work of Michael Faraday upon electro-magnetism and the conduction of electricity in solutions, as well as in the subsequent development of his ideas by J. Clerk Maxwell. Its corner-stone was laid by J. J. Thomson when, in 1898, he discovered the *electron*. The investigations of Maxwell had shown that light is probably an electrical wave-motion, and this conception was strongly confirmed by the discovery of the long electrical waves by H. R. Hertz in 1887. The idea of "a molecule of electricity" was clearly suggested by Maxwell, and the name "electron" was applied to the conception as early as 1881 by G. J. Stoney. The definite physical demonstration of its reality dates from the more recent work of Thomson, P. A. Lenard, H. A. Lorentz, and others, who have shown that electrons in their vibrations undoubtedly generate light.

Another line of discovery which has been of tremendous importance to the modern theory lies in the field of radio-activity, which was opened by the investigations of Henri Becquerel in 1896. The conception of the atom as the indestructible basis of *chemical* change was first systematically defended by John Dalton in 1808. The science of radio-activity has not only provided us with a new source of electrons, but it has led us to the conclusion that the

NOTE: The Section numbers coincide with the full-face index numbers in the text of Part I.

chemical atom, although a fundamental reality, is nevertheless destructible. Of late years the most important work in this new science has been done by Ernest Rutherford, whose treatise on the subject is now standard.

The discovery of "X Rays" by W. C. Roentgen in 1895 was another important event in the development of the modern conception of the constitution of matter. The problem as to their exact nature has only recently been settled, but with its solution have come remarkable advances in our knowledge of the structure of crystalline bodies.

During the past fifteen years a host of new workers have appeared and progress has been proportionately rapid. At the present time we seem to be on the verge of epoch-making discoveries with regard to the nature and laws of radiant energy (or light), which may bring about as fundamental a change in the ideas of ultimate physics as did the discovery of the electron and of the phenomena which it underlies. Besides this — the most recent development of all — in the theory of "isotopism" and "atomic numbers" new light is being thrown on the fundamental mystery of the periodic table of the chemical elements.

REFERENCES

An ably written sketch of the history of electricity by J. A. Flemming is to be found under "Electricity" in the 11th edition of the Encyclopaedia Britannica. The article "Atom," in the same work, may also be consulted to advantage in connection with the history of the theory of matter.

Section 2

METHODS OF DETERMINING ATOMIC SIZES

There are a great many possible ways of determining the approximate size of atoms and molecules, but those which are the simplest and most direct are unfortunately the least accurate.

Thin Films. — It is obvious that if the atoms have a permanent shape and volume they must be at least as small in diameter as the thinnest known films of matter are thick. When gold is flattened by the process of gold-beating the atoms are spread out over a surface greater than that which they previously covered. Now a sheet of the thinnest gold-leaf measures about one one-millionth of an inch in thickness so that the atoms of gold — which are among the largest known — must have a diameter at least as small as one one-millionth of an inch. However, we are familiar with liquid films which are much thinner than gold-leaf. The walls of soap-bubbles and the films produced by pouring oil in very small quantities upon water are sometimes as thin as one twenty-millionth of an inch, and consequently the diameter of the atoms which compose them cannot be greater than this figure.

Indirect Methods. — To arrive at more exact estimates of the size of atoms it is necessary to resort to calculation. Such a method of course involves some assumptions, but there are many different ways of calculating atomic sizes in which nearly as many different assumptions are employed, and as they all lead to substantially the same results they cannot be far from the truth. The facts upon which calculations of this sort have been based vary from the resistance offered to the passage of the electric current through metals and liquids, to the blue color of the sky.

The Number of Atoms in a Given Volume. — It is clear that if we were acquainted with the *number* of atoms contained in a given body we could specify an upper limit for the size of a single atom, by dividing the volume of the body as a whole by the number of atoms which it contained. Of course this calculation would not provide us with an

exact measure of the atoms themselves, because all of the space in the body is not occupied by the atoms. This is due in part to the fact that the atoms are separated under the influence of the constant vibratory motion which goes on among them, but it would also be true even if they were entirely quiescent, which would be the case at the so-called "absolute zero" of temperature, as explained further on in Part I. However, the atoms alone could not be larger than the size determined by such a calculation, and if the data upon which it was based were taken from a solid substance at or near absolute zero it would come very close to an accurate measure of the actual atomic size.

Now it happens that it is relatively easy to discover the number of atoms which are contained in a given weight of almost any substance. One very simple and accurate method of doing this is to weigh the amount of the substance which is deposited out of solution by the passage of a certain quantity of electricity. Each atomic particle thus deposited carries with it a definite and known quantity of electricity, the natural unit of electricity or some simple multiple of this unit.[1] The number of times this unit is contained in the quantity of electricity which has passed gives us a measure of the number of atoms in the amount of substance which has been deposited by the current. Since this substance can be collected and its volume determined, we are able to specify the number of atoms contained in a given volume of the substance in question, although the problem is slightly more complex than we have represented it.

From this we can calculate easily the upper limit of atomic size to which we have referred.

[1] Which happens to be the charge borne by the electron, and which can be determined by other means.

Recently it has been found possible to count individually the helium atoms (see Section 48), which are shot off from radio-active substances, so that after a measurable amount of this gas has collected, the number of atoms (77 billion billion per cubic inch) of which it is made up is accurately known.

Other Methods: the Atoms of Gases. — Another fairly direct way of getting the magnitude of atoms depends upon a measurement of the speed at which atoms move through a liquid or a gas under the influence of a known force. The smaller the particles into which a given quantity of matter is divided the more slowly it will move through a fluid under the action of a fixed force. Everybody is familiar with this fact in the case of falling dust particles, which are all acted upon by one force, gravity. The larger ones settle very rapidly, whereas the small particles may remain apparently motionless in quiet air for a long time. Under the right conditions atoms can be made to move through liquids and gases under forces as definitely known as that of gravity, and although these substances are themselves made up of atoms the nature of the resistance which the moving atoms encounter is probably not very different from that which would be offered to the passage of larger bodies. Of course we cannot measure the rate of motion of single atoms, but we can determine that of large numbers of them, which is equally satisfactory to our purpose. Knowing the speed of the travelling atoms and the magnitude of the forces which are propelling them, we can easily calculate their diameters, which according to this method turn out to be about one one-hundred-millionth of an inch.

Still more accurate methods are known for the calculation of atomic sizes, but most of these are dependent upon complex considerations into which we cannot enter

here. For example, the size of the atoms of a gas can be calculated from the rate at which heat is conducted through the body of the gas. Heat consists in the rapid random motion of the gas molecules, and it is clear that the larger these molecules are, the more they will impede each other's motion and, consequently, the more slowly this motion will be transferred from one part of the gas to another. But such a transfer is identical with the conduction of heat. If we combine our knowledge of the rate of conduction with that of the number of molecules contained within a given volume of the gas we can calculate the size of the molecules themselves. In the case of simple substances, molecular and atomic sizes are of the same order of magnitude.

Other methods of figuring atomic sizes depend upon measurements of the so-called "viscosity" of gases, or their internal friction. It is also possible to get a very exact idea of the diameter of the gas molecules by studying the deviations from the well-known "law of Boyle" (see Section 18 below), which states that the volume of a gas is inversely proportional to the pressure under which it is confined. These deviations are due to the influence of the volume of the atoms themselves upon that of the gas as a whole. The atoms in most gases are very far apart compared with their sizes, but as the gas is compressed — that is, as the atoms are forced nearer and nearer together — the atomic volume begins to make itself felt, and this fact provides us with a basis upon which to calculate that volume. Another well-known method is founded upon the rates at which gases "diffuse" into each other, and modern studies in electricity have yielded other very exact means of determining the diameters of atoms. The new science of radio-activity has also contributed to our knowledge of atomic sizes by

furnishing the experimenter with individual atoms bearing electrical charges to make them conspicuous, and moving at almost inconceivably high velocities.

Agreement of Results. — The results of these diverse methods of discovering the magnitude of atoms are in a harmony so substantial that it is practically impossible to doubt their truth. The diameter of the smallest atoms must be closely in the neighborhood of one three-hundred-millionth of an inch, and that of the largest cannot be many times this. What may perhaps be called "the realm of atomic magnitudes" is accordingly very definite and limited.

REFERENCES

For a more detailed discussion of the means by which the sizes of atoms and molecules are calculated the reader may consult:

A. D. Risteen's "Molecules and the Molecular Theory," 1895, pp. 133–151.

A list of specific molecular diameters, calculated from modern measurements is given by W. Sutherland in the English *Philosophical Magazine* for February, 1908, vol. 17, pp. 320–321. A very simple discussion of atomic sizes will be found in A. E. Dolbear's "Matter, Ether, and Motion," enlarged edition, 1894, pp. 8–26.

On molecular volumes and their calculation, see W. Nernst's "Theoretical Chemistry," (Eng. Trans.), pp. 304–307.

Section 3

ATOMS, COLLOIDS, AND THE MICROSCOPE

To make a single atom visible to the eye we should require a microscope capable of enlarging the apparent size of objects nearly a million times. The so-called "ultra-microscope" has a power closely approaching this, and still more powerful instruments might be built if optical principles did not interfere. Objects very much smaller than light waves will not reflect light in the usual way, *i.e.*, so that their surfaces can be seen. However, they are often detectable under the ultra-microscope as

minute luminous specks or points. Particles having a diameter of about three millionths of an inch have been detected by means of the ultra-microscope. This is approximately two hundred times the diameter of the average atom. Whether or not we shall ever be able to prove the existence of atoms and molecules by sight is a question which must be decided by the progress of optical invention, but it is well to bear in mind the fact that even now the limits of visibility lie not very far from the realm of atomic sizes.

The particles seen under the ultra-microscope are those characteristic of so-called *colloidal* substances. There is a continuous gradation of sizes among such particles, from those of strictly molecular magnitude up to the very much larger granules which are found in an "emulsion" or a "suspension." There is thus no sharp line dividing colloidal particles from large molecules but, nevertheless, colloidal substances have remarkable properties which distinguish them from strictly molecular, or "crystalloid" bodies. These properties are exhibited most distinctly in aqueous solution or suspension, and include such phenomena as coagulation and gelatination. Most of the substances characteristic of living organisms are in the colloidal state, and it is almost certain that life would be impossible without colloids. However, the fundamental peculiarity about colloids, is simply their degree of subdivision, or "dispersion," as it is sometimes called.

REFERENCES

On the use and results of the ultra-microscope see R. Zsigmondy's "Colloids and the Ultra-Microscope" (Eng. Trans.), 1909, esp. page 122 on the limits of visibility.

For a popular discussion of the questions above raised see A. E. Dolbear's "Matter, Ether, and Motion," enlarged edition, 1894, pp. 8–26.

Section 4

THE SHAPE OF ATOMS

Why Atoms are Supposed to be Spherical. — It is obvious that the shape of an atom or molecule will materially affect certain of the properties of the bodies of which it forms a part. For instance, if the molecules of gases had the form of long cylinders or rods all of the properties of the gases which depend upon the ease of movement of the molecules among themselves would be different from what they would be if the molecules were spherical. Indeed, it is impossible to calculate the characteristic "constants" of gases on the basis of the molecular theory without the use of some definite assumption about the shape of its molecules. The one usually made is that the molecules are *spherical*, and since it leads to general results which are in harmony with the facts it must be nearly correct.

When a number of bodies are thrown together in a heap the size of the heap will depend not only upon the volume of the individual bodies and upon the number present, but also upon their *shape*. Thus, if they were all cubes and were packed neatly together they would fill the whole space marked off by the "heap." However, if they were spheres they could not possibly be arranged so as to take up all of this space.

Now we have a number of means of estimating the volume of the individual atoms or molecules of substances, which are independent of any knowledge of the volume occupied by large masses of these substances. If we assume that the molecules are spherical, therefore, we can calculate the amount of space which should be filled by a body containing a given number of them under certain

conditions, as for example those which hold at absolute zero, when the molecules are motionless. We can then compare this volume with that actually occupied under these conditions by a body made up of the same number of molecules of the special substances which we are studying. If the two are essentially the same we shall have some reason for supposing that our original assumption concerning the roundness of the molecules or atoms was correct. Calculations of this sort have been made and indicate that most atoms are either spherical or are slightly flattened spheres.

The "Saturnian Atom." — Although it is desirable for purposes of clearness to think of the atom as possessing a definite surface having a definite contour, it is also important to bear in mind the fact that the resemblance between an atom and a solid ball probably amounts to little more than an analogy. As represented in the figures in the text, the surfaces or "edges" of an atom are probably ill defined, and they may even be changeful. Certain modern considerations — which are touched upon in Section 53 — make it seem altogether likely that the atom is really a system of rapidly rotating particles which are very much smaller than the atom itself. If this theory should prove to be true the size and shape of the atom would merely be those of the "orbits" of the outermost of these rotating particles, just as the size and shape of the solar system depends upon those of the orbits of the outermost planets.

Some of the most recent studies on the shape of the atoms have been made by R. D. Kleeman.

REFERENCES

Kleeman's discussion of atomic shapes is rather difficult, but can be found in the *Philosophical Magazine* for July, 1910, vol. 20, pp. 229–238.

As an illustration of the manner in which the assumption of the sphericity of the atom or molecule enters into the theory of gases see: W. P. Boynton's "Applications of the Kinetic Theory," (1904) Chapter III.

A very popular discussion of "Solar system" conception of the atom is given in Chapter IV of C. R. Gibson's "Scientific Ideas of To-day," (1909) pp. 52–58.

Section 5

SPECIES OF ATOMS; ATOMIC WEIGHTS, AND ATOMIC VOLUMES

The official table of the chemical elements now contains eighty-three names, each of which corresponds with a particular species of atom. In addition to these we must include in our list of atomic species the many unstable elements, which have been discovered by the new science of radio-activity.

The first table below gives the names of the recognized chemical elements with their "atomic weights" on the basis of oxygen = 16. The second table performs the same service with respect to the new radio-active elements, several of which are also included in the first table.

TABLE I. THE CHEMICAL ELEMENTS

Atomic Number	Name of Element	Symbol	Atomic Weight	Nature under Ordinary Conditions	Date Discovered
1	Hydrogen	H	1.008	Very light gas, chemically active	1766
2	Helium	He	3.99	Very light gas, chemically inert	1868
3	Lithium	Li	6.94	Light alkali-forming metal	1817
4	Glucinium	Gl	9.1	Light metal, resembling zinc	1828
5	Boron	B	11.0	Non-metal, occurs in "borax"	1808
6	Carbon	C	12.00	Non-metal (charcoal and diamond)	P
7	Nitrogen	N	14.01	Atmospheric gas, inert	1772
8	Oxygen	O	16.00	Atmospheric gas, chemically active	1774
9	Fluorine	F	19.0	Excedingly corrosive gas	1810
10	Neon	Ne	20.2	Inert atmospheric gas	1898
11	Sodium	Na	23.00	Alkali metal, occurs in "salt"	1807
12	Magnesium	Me	24.32	White, combustible metal	1808
13	Aluminium	Al	27.1	Light, white metal	1828
14	Silicon	Si	28.3	Hard, semi-metallic substance	1828
15	Phosphorus	P	31.04	Inflammable non-metal	1738
16	Sulphur	S	32.07	Inflammable non-metal	P
17	Chlorine	Cl	35.46	Yellow, corrosive gas	1810
18	Argon	A	39.88	Inert atmospheric gas	1894

19	Potassium	K	39.10	Alkali metal, occurs in "potash"	1807
20	Calcium	Ca	40.07	Alkaline earth, occurs in "lime"	1808
21	Scandium	Sc	44.1	Metal found in rare earths	1879
22	Titanium	Ti	48.1	Metal found in rare earths	1795
23	Vanadium	V	51.0	Metal found in rare earths	1801
24	Chromium	Cr	52.0	Hard metal forming highly colored compounds	1797
25	Manganese	Mn	54.93	Grayish metal	1774
26	Iron	Fe	55.84	Grayish metal	P
27	Cobalt	Co	58.97	Silvery-white metal	1733
28	Nickel	Ni	58.68	Hard, silvery-white metal	1751
29	Copper	Cu	63.57	Reddish-yellow metal	P
30	Zinc	Zn	65.37	Silvery-white metal	1520
31	Gallium	Ga	69.9	Hard, grayish-white metal	1875
32	Germanium	Ge	72.5	Grayish, metallic solid	1886
33	Arsenic	As	74.96	Brittle, steel-gray semi-metallic subs.	1649
34	Selenium	Se	79.2	Sulphur-like solid	1817
35	Bromine	Br	79.92	Heavy, corrosive, red liquid	1826
36	Krypton	Kr	82.92	Inert atmospheric gas	1897
37	Rubidium	Rb	85.45	Soft, white, alkali-metal	1863
38	Strontium	Sr	87.63	Alkaline-earth metal	1808
39	Yttrium	Yt	89.0	Dark gray metal	1826
40	Zirconium	Zr	90.6	Hard, brittle, iron-gray metal	1824
41	Columbium	Cb	93.5	Steel-gray metal	1846
42	Molybdenum	Mo	96.0	Metal resembling iron	1782
44	Ruthenium	Ru	101.7	Platinum-like metal	1844
45	Rhodium	Rh	102.9	"Infusible," silvery metal	1804
46	Palladium	Pd	106.7	Fusible, platinum-like metal	1803
47	Silver	Ag	107.88	Metal, of familar properties	P
48	Cadmium	Cd	112.40	White, malleable, zinc-like metal	1817
49	Indium	In	114.8	Soft, malleable, zinc-like metal	1863
50	Tin	Sn	119.0	Silver white, very malleable metal	P
51	Antimony	Sb	120.2	Brittle, white, crystalline metal	1450
52	Tellurium	Te	127.5	White, semi-metallic solid	1782
53	Iodine	I	126.92	Volatile, brown, non-metallic solid	1811
54	Xenon	Xe	130.2	Inert atmospheric gas	1898
55	Caesium	Cs	132.81	Soft alkali-metal	1860
56	Barium	Ba	137.37	Soft silver-white alkali-earth metal	1808
57	Lanthanum	La	139.0	Malleable metal found in rare earths	1841
58	Cerium	Ce	140.25	Rare-earth metal resembling iron	1801
59	Praseodymium	Pr	140.6	Rare earth metal	1885
60	Neodymium	Nd	144.3	Rare earth metal	1885
62	Samarium	Sa	150.4	Rare earth metal	1879
63	Europium	Eu	152.0	Rare earth metal	1901
64	Gadolinium	Gd	157.3	Rare earth metal	1886
65	Terbium	Tb	159.2	Rare earth metal	1843
66	Dysprosium	Ds	162.5	Rare earth metal	1907
67	Holmium	Ho	163.5	Rare earth metal	1886
68	Erbium	Er	167.7	Rare earth metal	1843
69	Thulium	Tm	168.5	Rare earth metal	1879
70	Ytterbium	Yb	172.0	Rare earth metal	1878
71	Lutecium	Lu	174.0	Rare earth metal	1906
73	Tantalum	Ta	181.5	Hard, silvery, ductile metal	1863
74	Tungsten	W	184.0	Brittle, very "infusible," metal	1783
76	Osmium	Os	190.9	Blue-gray resistant metal	1804
77	Iridium	Ir	193.1	Brittle, "infusible," metal	1804
78	Platinum	Pt	195.2	Silvery, "infusible," metal	1560
79	Gold	Au	197.2	Chemically resistant metal	P
80	Mercury	Hg	200.6	Liquid, silvery metal	300 B. C.
81	Thallium	Tl	204.0	Soft, whitish metal	1861
82	Lead	Pb	207.10	Soft, bluish-white metal	P
83	Bismuth	Bi	208.0	Very brittle reddish-white metal	1450
86	Niton	Nt	222.4	Inert gas (radium emanation)	1900
88	Radium	Ra	226.4	Radio-active alkaline-earth metal	1898
90	Thorium	Th	232.4	Heavy, rare-earth metal	1898
92	Uranium	Ur	238.5	Hard, white, malleable metal	1780

The atomic weights above are those given by the "International Committee on 'Atomic Weights,' for 1914." "P" in the last column stands for "prehistoric."

TABLE II. THE RADIO-ELEMENTS.

URANIUM-RADIUM SERIES

Atomic Number	Name of Element	Atomic Weight	Chemical Analogue
92	Uranium 1	238.15	Tungsten (h)
90	Uranium X_1	234	Thorium (i)
91	Uranium X_2	234	Tantalum (h)
92	Uranium 2	234	Uranium 1 (i)
90	Ionium	230	Thorium (i)
88	Radium	225.95 (Hönigschmid)	Barium (h)
86	Radium Emanation (Niton)	222	Xenon (h)
84	Radium A	218	Polonium (i)
82	Radium B	214	Lead (i)
83	Radium C	214	Bismuth (i)
84	Radium C'	214	Polonium (i)
81	Radium C_2	210	Thallium (i)
82	Radium D (Radio-Lead)	210	Lead (i)
83	Radium E	210	Bismuth (i)
84	Radium F (Polonium)	210	Tellurium (h)
82	Radium G (probably Lead)	207.10 (?)	

THORIUM SERIES

90	Thorium	232.4	Cerium (h)
88	Meso-Thorium 1	228	Radium (i)
89	Meso-Thorium 2	228	Actinium (i)
90	Radio-Thorium	228	Thorium (i)
88	Thorium X	224	Radium (i)
86	Thorium Emanation	220	Niton (i)
84	Thorium A	216	Polonium (i)
82	Thorium B	212	Lead (i)
83	Thorium C	212	Bismuth (i)
84	Thorium C'	212	Polonium (i)
81	Thorium D	208	Thallium (i)

ACTINIUM SERIES

89	Actinium	230 (?)	Lanthanum (h)
90	Radio-Actinium	230 (?)	Thorium (i)
88	Actinium X	226 (?)	Radium (i)
86	Actinium Emanation	222 (?)	Niton (i)
84	Actinium A	218 (?)	Polonium (i)
82	Actinium B	214 (?)	Lead (i)
83	Actinium C	214 (?)	Bismuth (i)
81	Actinium D	210 (?)	Thallium (i)

Only ten of the thirty-five substances named above are believed to represent chemically new atomic species. The atomic weights of only a few of them are accurately

known; those of the others are estimated on the basis of the theory of radio-active disintegration. The last column gives the name of another element to which the given element is closely similar. In the cases marked (i) the two elements are "isotopic" *i.e.*, although of different atomic weight or radio-activity, are identical in chemical character. (h) indicates a "homologue" in the periodic table.

The weights of the atoms are expressed in terms of the weight of the lightest atom, namely that of hydrogen.[1] Thus, when we say that the "atomic weight" of oxygen is 16 we mean that an atom of oxygen weighs 16 times as much as an atom of hydrogen.

Method of Finding Atomic Weights. — The methods by which the relative weights of the atoms are determined are not difficult to understand. Suppose, for example, that the chemist desires to learn the atomic weight of the element *chlorine*. He knows by experiment that chlorine gas will combine with hydrogen gas in definite proportions to form hydrochloric acid. When he analyzes this compound he finds that it contains 35.18 parts of chlorine by weight to one part of hydrogen. Consequently on the assumption that the molecule of hydrochloric acid is made up of one atom of hydrogen and one atom of chlorine, he is able to determine the atomic weight of chlorine as 35.18, assuming that of hydrogen to be unity (or as 35.46 on the basis of the weight of oxygen taken equal to 16). Similar measurements can be made of the proportions by weight in which other elements combine with hydrogen, and these will furnish a basis for the calculation of their atomic weights also.

[1] As a matter of fact, the unit atomic weight now generally used is $\frac{1}{16}$ the weight of the oxygen atom, but this differs only slightly from that of the atom of hydrogen.

It may well be asked how it is that the chemist can know the number of atoms of particular elements which are contained in a given compound unless he first knows the atomic weights of these elements. For example, the compound, water, is made up of one part of hydrogen to eight of oxygen, but instead of stating on the basis of this fact that the atomic weight of oxygen is 8 the chemist comes to the conclusion that water contains two atoms of hydrogen, so that the atomic weight of oxygen is 16. One of the things which leads him to this conclusion is the fact that if he takes the atomic weight of oxygen as 8, he will soon find it necessary to suppose that the molecules of certain substances other than water, contain oxygen in less than atomic quantities, which is impossible. Thus by comparing many different results derived from the analysis of different compounds containing the same elements, the chemist is led finally to the selection of relative weights in harmony with the atomic theory.

However, there are other considerations which lead to similar results. It is a well-known principle that equal volumes of all gases under the same conditions contain the same number of molecules, and from this fact it follows that if we weigh equal volumes of different gases under these constant conditions we will obtain, immediately, the relative weights of their constituent *molecules*. Thus, when water is broken up into hydrogen and oxygen gas it yields two volumes of the former for one of the latter, a fact which seems to indicate that twice as many atoms of hydrogen are present in a molecule of water as there are atoms of oxygen. It is obvious that the "molecular weights" of all substances which are capable of being converted into a gas can be found by measuring the weight of a unit volume of this gas under standard conditions. Such a knowledge of the relative weights of

the molecules composing a compound will clearly be of the utmost value in the determination of the weights of the atoms of which they in turn are composed.

Some of the elements do not combine with hydrogen to form substances which it is convenient to analyze. However, the atomic weights of such elements may be found indirectly by studying the ratios in which they unite with other elements of known atomic weight. Thus, most elements which have slight affinity for hydrogen combine very readily with oxygen, and since hydrogen also forms a definite compound with oxygen, this latter element constitutes a connecting link between hydrogen and the element whose atomic weight we desire to determine.

Atomic Weights and Atomic Volumes. — The idea has recently been advocated by J. Traube that a simple and definite relationship exists between the size of an atom of any element and its weight. The volume of the atom appears to vary approximately as the square-root of its weight. This means that the diameter of a spherical atom would be proportional to the sixth root of its weight, so that although atomic diameters vary rather widely among the lighter elements the diameters of the heavier atoms are very nearly alike. This law connecting atomic weights and volumes is based upon measurements of essentially the same character as those which we have discussed in Section 2, above. However, it appears also to be in harmony with certain phenomena in radio-activity which seem to depend upon the volume of the atoms composing a body.

REFERENCES

A table of the radioactive substances, with their properties, will be found in Kaye and Laby's "Tables of Physical and Chemical Constants" (1911), pp. 107–108. A more elaborate discussion will be found in Ernest Rutherford's "Radio-Active Substances and Their Radiations," (1913). For the most recent developments see

the 1915 edition of Frederick Soddy's "The Chemistry of the Radio-Elements," pp. 70–142.

On the choice of atomic weights, see Wilhelm Ostwald's "Outlines of General Chemistry" (1890), Part I, Book VI, Chap. I, pp. 178–182.

An excellent detailed discussion of the determination of atomic weights also appears in H. C. Jones' "The Elements of Physical Chemistry" (1902), pp. 4–18.

Section 6

THE PERIODIC TABLE OF THE ELEMENTS

Systematic Relations between Elements. — We might conceive a state of affairs in which all of the chemical elements would be wholly different from one another, but everyone knows that this is not actually the case in nature. When the elements are compared it is found that curious resemblances exist among them, and moreover that these resemblances depend in some way upon the *atomic weights* of the elements which are compared. Take for example the three elements, chlorine, bromine and iodine, which everyone who has handled them in the chemical laboratory knows to be curiously similar. We find upon investigation that the atomic weight of bromine is approximately the arithmetic mean between those of chlorine and iodine. Several other almost equally striking "triads" (or groups of three) of this character can be pointed out.

The systematic distribution of the properties of the elements becomes still more obvious when we arrange them in order of their atomic weights, as in the table below. It then appears that, with certain exceptions, every eighth element in the series possesses similar properties. This fact is indicated in the table by placing the names of the elements which resemble each other in the same

vertical columns. Such elements are said to belong to the same "family," or "group," and it will be observed that there are eight families of this sort in the table. All members of one family tend to have the same combining power, or "valency" (see Section 34, below), and their compounds with other elements tend to resemble each other closely. Thus in the second column, lithium, sodium, potassium, rubidium and cæsium are all metals forming strongly alkaline compounds with hydrogen and oxygen, of which ordinary "washing soda" is an example. Each of these elements has normally a combining power of one, that is one atom of each of them will unite with one atom of such an element as chlorine, which in turn unites with one atom of hydrogen. As we pass from left to right in the table the combining power of the represented elements increases and then diminishes, periodically. Copper, silver and gold which are classed in the second family differ from the other five elements in the family but form a transition group to those in the third column.

Nearly all of the properties of the elements are found to depend upon their position in the "periodic table," as the arrangement which we are discussing is called. This is true not only of the chemical properties but also of such physical properties as melting point, specific gravity, etc.

The elements of a single horizontal line are said to be members of the same "series" or "period." The table is called "periodic," for the reason that as we pass from one member of a "series" to the next, the properties of the elements first depart from those of the element with which the series started and then alter their course of variation to return to properties closely resembling those of the first member of the series.

Defects in the Table. — It will be noted that certain blank spaces occur in the table as we have represented it. *These spaces are left vacant for occupancy by elements as yet undiscovered.* When the table was first constructed by Mendelejeff there were more empty spaces in it than there are now. The faith of chemists in the table was so great that they were led to predict the discovery of elements having atomic weights permitting them to fit into these vacant spaces, and they even went so far as to specify the properties of these elements and of their compounds. In several cases these predictions have since been fulfilled by the actual discovery of the elements in question.

As can be seen by inspection the periodic table is not a perfect system for the classification of the elements, or if so is far from simple in many respects. All of the elements do not fit nicely into their places, this being especially true in the case of the nine which are represented in the ninth column. Here we have groups of closely similar elements which are of about the same atomic weight and which refuse to fit into the scheme of "families."

Significance of the Periodic Relationships. — The exact meaning of the definite relationships between the elements which are proven by the periodic table to exist, is at present largely a mystery. However, there can be little doubt that the demonstrated resemblances depend in some way upon the constitution of the atoms of which the elements are made up. (See Section 53, below.) The fact that the properties of the elements appear to be determined (at least approximately) by the relative weights of their atoms clearly suggests this interpretation, for if the atoms have a definite internal structure and if the units of this structure are similar for all of the atoms, increasing complexity would necessarily mean increasing

atomic weight. If the units of structure were not similar we should hardly expect to find the systematic resemblances which actually exist.

One of the earliest theories to make use of the idea of a single substance or "protyle" common to all of the chemical elements was that of Prout, who suggested in 1815, that the heavier atoms might be clusters or condensations of various numbers of hydrogen atoms. This hypothesis received support from the fact that a large number of atomic weights — more than would be expected as a result of chance — are approximately integral multiples of the weight of the hydrogen atom. However, accurate determinations of the weights which fail to approximate such values did not substantiate Prout's original belief that the deviations were due to experimental errors. Consequently, in its primitive form, at least, the theory had to be rejected.

The new facts brought to light in the study of radioactivity (see Section 46, below), however, make it practically certain that if hydrogen is not one of the fundamental bricks of which the heavier atoms are built, just such a rôle is played by the element *helium*. In radioactivity, atoms break down into others of less weight, and this loss of weight always occurs in single decrements of four units. This is the mass of the helium atom, and it has been proved that every change in mass of a radioactive substance is accompanied by the generation of helium. Besides this, it has been pointed out that a difference of four units between neighboring members in the periodic table is a very common one.

The Nucleus Theory of the Atom, and Isotopes. — However, this last-mentioned rule is far from being strictly obeyed, and it is certain that hydrogen itself cannot be made up of helium. At the present time there is current

TABLE III. PERIODIC TABLE OF THE ELEMENTS

	E_0	$E^{I}Cl$ E^{I}_2C	$E^{II}Cl_2$ $E^{II}O$	$E^{III}Cl_3$ $E^{III}_2O_3$	$E^{IV}H_4$ $E^{IV}O_2$	$E^{III}H_3$ $E^{V}_2O_5$	$E^{II}H_2$ $E^{VI}O_3$	EH $E^{VII}_2O_7$	$E^{VIII}O_4$
1 Hydrogen 1.008	2 Helium 4	3 Lithium 7	4 Glucinium 9	5 Boron 11	6 Carbon 12	7 Nitrogen 14	8 Oxygen 16	9 Fluorine 19	
	10 Neon 20	11 Sodium 23	12 Magnesium 24.4	13 Aluminium 27	14 Silicon 28.4	15 Phosphorus 31	16 Sulphur 32	17 Chlorine 35.5	
A	18 Argon 39.9	19 Potassium 39	20 Calcium 40	21 Scandium 44	22 Titanium 48	23 Vanadium 51	24 Chromium 52	25 Manganese 55	26 Iron 56 27 Cobalt, 59 28 Nickel 58.7
B		29 Copper 63.6	30 Zinc 65.4	31 Gallium 70	32 Germanium 72.5	33 Arsenic 75	34 Selenium 79.2	35 Bromine 80	
A	36 Krypton 87.8	37 Rubidium 85.4	38 Strontium 87.6	39 Yttrium 89	40 Zirconium 90.6	41 Columbium 94	42 Molybdenum 96	43 Unknown	44 Ruthenium, 101.7 45 Rhodium 103 46 Palladium 106.5

B		47 Silver 108	48 Cadmium 112.4	49 Indium 115	50 Tin 119		51 Antimony 120	52 Tellurium 127.6	53 Iodine 127			
A	54 Xenon 128	55 Caesium 133	56 Barium 137.4	57 Lanthanum 139	58–71 Cerium, etc. [140–174 incl.		73 Tantalum 181	74 Tungsten 184	75 Unknown	76 Osmium, 191	77 Iridium 193	78 Platinum 195
B		79 Gold 197	80 Mercury 200	81 Thallium 204	82 Lead 207		83 Bismuth 208	84 Polonium 210	85 Unknown			
A	86 Niton 222	87 Unknown	88 Radium 226.5	89 Actinium (?)	90 Thorium 232.5		91 Uranium X2 234	92 Uranium 238.5				

The symbols in the first line represent the typical compounds (See Section 7 below), formed by the elements in the several columns, and show the characteristic valencies of the elements in question. Thus in the fifth column the elements have a constant valency of four, combining with four atomic parts of hydrogen or two of oxygen. Each vertical column comprises a "group," each horizontal column a "period." The numbers below the names of each of the elements give approximately their atomic weights, those above, their "atomic numbers."

a definite and well-grounded conception of the structure of the hydrogen atom (Cf. Section 53), in accordance with which the latter is composed of a single minute particle of negative electricity — an electron — and a very much smaller particle of positive electricity about which the electron revolves. Practically the entire mass of the atom is concentrated in the positive "nucleus," as it is called. The more ponderous atoms are supposed to be formed from a larger number of positive and negative particles, according to their respective weights. The positive particles are always condensed into very small nuclei, together with a portion of the electrons, and it is probable that, in the case of the heavier elements at least, the helium atom is an important secondary unit in the structure of these nuclei.

Within the past few years the study of radio-active substances has brought out facts which indicate that the fundamental principle of the periodic table — that the chemical properties of an element are determined by its atomic weight — is only approximately true. As already mentioned (Section 5, above), radio-active elements — isotopes — are known which differ in atomic weight but have identical chemical properties. On the other hand, there are elements of the same atomic weight which show radical differences chemically. The explanation of this very important discovery apparently lies in the suggestion that the chemical nature of an atom depends not directly upon its weight but upon its electrical structure, which to a limited extent may change practically independently of the weight. Of this more will be said in the appropriate context. (See Section 53.)

Chemical Elements as Atomic Mixtures. — The existence of "isotopes" among the radio-elements suggests their presence in other parts of the periodic table. In

the latter case there appears a possible solution of the difficulty that the majority of the atomic weights are not *accurate* multiples of that of hydrogen. It is conceivable, even probable, that the chemical elements — which we have previously regarded as individual species of matter — are in reality only types, or classes, of such individuals, all of the members of a single class being indistinguishable and non-separable from each other by purely chemical means. In this case the atomic weights given in Table I (Section 5) must represent averages of the relative weights of a number of chemically similar atoms with different masses, which may be present in standard chemical preparations in nearly constant but in unequal amounts. If this is true it is not surprising that our empirically determined atomic weights do not have integral values.

The above speculations receive support from certain experiments by J. J. Thomson, not depending in any way upon radio-active phenomena, which suggested that the inert atmospheric gas, *neon*, is really made up of two isotopic constituents, one of atomic weight about 20 and the other (meta-neon) about 22. F. W. Aston, following out this clue, found that by the use of physical methods relying on the relative rates of diffusion of the two components, pure atmospheric neon could actually be separated into two gases of different density. Careful comparisons of samples of lead derived from geologically different sources indicate that this element, also, may be a mixture of isotopes, an idea which is strongly suggested by its relation with the radio-active substances.

All of these results should be accepted with reservations on account of their novelty, but it must be admitted that they open a vista of new insights into the meaning of the periodic table.

REFERENCES

For a detailed discussion of the periodic table see Harry C. Jones, "The Elements of Physical Chemistry" (1902), pp. 18–37.

A more popular exposition can be found in R. K. Duncan's "The New Knowledge" (1905), Part II.

See also W. Nernst's: "Theoretical Chemistry," Eng. trans. from 6th German ed. (1911), pp. 178–190.

On "isotopes," see Frederick Soddy's "The Chemistry of the Radio-Elements" (1915), Part I, pp. 50–56; Part II, complete. Also an article by E. Rutherford: "The Constitution of Matter," *Popular Science Monthly*, August, 1915.

Section 7

THE ARRANGEMENT OF THE ATOMS IN THE MOLECULE

Atoms may group themselves to form molecules of almost any conceivable shape. The properties of the substance which such molecules compose seem to depend in large part upon the manner in which the atoms are combined, that is, not only upon the number and nature of the atoms but upon their *geometrical arrangement* within the molecule.

To show what a great variety of substances can be formed by different modes of combination of the same elements it may be stated that about two hundred thousand distinct compounds of the element carbon are now known, most of which are with only three other elements: hydrogen, oxygen, and nitrogen. These substances belong to the class of "organic" compounds, so called for the reason that many of them are essential in the chemical structures and changes of living organisms. There are undoubtedly thousands, if not millions, of specific chemical substances in living bodies which are

built up from the same four elements but which have not yet been separated out and analyzed.

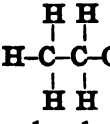
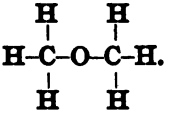
The element carbon is remarkable on account of the very large number of compounds which it can form, but the other elements also enter into the composition of a great variety of different substances. Each of these substances, organic or inorganic, possesses characteristic properties which distinguish it more or less sharply from all other substances.

Isomers and Structural Formulæ. — That the differences which exist in the properties of substances must depend at least in part upon the arrangement of the atoms within the molecule is proved by the fact that compounds exist which have quite different properties but exactly similar numbers and kinds of constituent atoms. Such cases are quite common in organic chemistry, and the substances involved are known as "isomers." Thus the organic chemist is acquainted with twenty-six different compounds which contain four atoms of carbon, six of hydrogen and three of oxygen, and with one hundred and fifty-seven which are composed of ten atoms of carbon and sixteen of hydrogen.

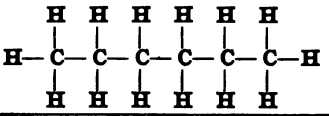
It is customary for the chemist to represent the make-up of a compound by means of a so-called "chemical formula" which shows in a simple way the constitution of the molecules of the substance. The formula of water, H_2O, may be taken as a simple example. This formula states that a molecule of water is made up of two atoms of hydrogen, H, combined with one atom of oxygen, O. As an example of a more complex formula we may consider that of alcohol, C_2H_6O, or that of the coal-tar oil, benzene, C_6H_6, in both of which C stands for the element, or the atoms of carbon.

There is only one substance which has the formula

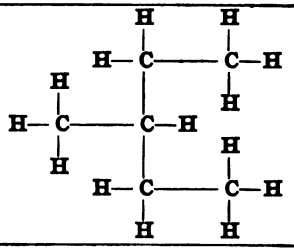
H_2O, so that no confusion can arise as to the meaning of this formula. It always stands for water. However, at least two substances are known which have the formula C_2H_6O, namely ordinary alcohol, and a gas called "methyl ether," which is closely similar to the ether employed in surgical operations. It is obvious that if we desired we could write the formula of water as H–O–H, in order to show the probable manner in which the atoms are combined in the molecule, but although this is not required in the case of water it is found necessary in the case of alcohol, and other substances which have isomers. Such a formula is called "structural" or "graphical" because it is a simple drawing representing the supposed arrangement of the atoms in the molecule of a substance. These formulæ can be constructed by studying the chemical relationships which exist between different compounds, and when thus evolved they not only enable us to distinguish theoretically between isomers, but also explain the differences which are found in their properties. However, as we shall see, their utility is not limited to the study of isomerism, for it is obvious that the more exact is our knowledge of the structure of different molecules the clearer will be our ideas concerning the changes which are liable to occur in these molecules.

A study of the manner in which alcohol can be built up from its elements leads us to assign to it the structural formula:  The substance "methyl ether," on the other hand, which we have mentioned as an isomer of alcohol, proves to have the formula: 

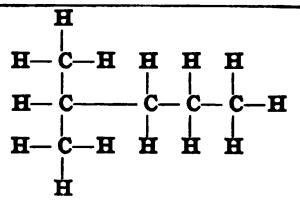
Normal Hexane



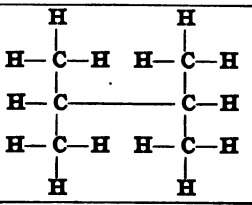
Methyldiethyl Methane



Dimethylpropyl Methane



Dimethylisopropyl Methane



Trimethylethyl Methane

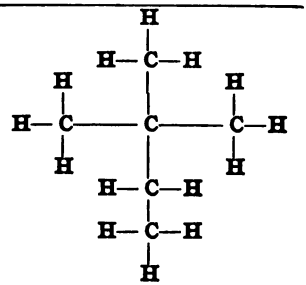


Fig. 12

FIVE ISOMERIC HYDROCARBONS HAVING THE CONSTITUTION C_6H_{14}

These chemical formulæ represent the supposed structure of the molecules of five distinct substances all of which contain the same number of hydrogen and of carbon atoms.

It is easy to see why the decomposition of the two molecules thus represented should lead to different results in spite of the fact that identically the same atoms are present in each case. We believe that these formulæ give a partial representation of the actual arrangement of the atoms in the molecules of alcohol and methyl ether respectively.

Figure 12 gives the graphical formulæ of five isomeric hydrocarbons each made up of six atoms of carbon, and fourteen of hydrogen. Although the formulæ show certain general resemblances, the five structures are nevertheless quite distinct. The resemblances correspond with an actual physical similarity of the substances, which causes them to be grouped in the same general class, but within this class the substances show a perfectly clear chemical individuality. Many other examples of this principle that the nature of a chemical substance depends upon the exact geometric structure of its molecules could easily be found.

The "Benzene Ring." — The approximate truth of the representations of the structure of molecules which are given by the structural formulæ now in use among chemists, is attested by such cases as that of the formula of *benzene*, the coal-tar oil of which we have spoken above. The six carbon atoms are supposed to be arranged in a molecule of this substance in the form of a ring, and to each of them is attached one of the hydrogen atoms. This formula is shown in Figure 13, (a). Each of the hydrogen atoms in the molecule can be replaced by atoms of other elements, as for example chlorine atoms, and for every new and different molecule thus produced there should exist a correspondingly distinct substance, which

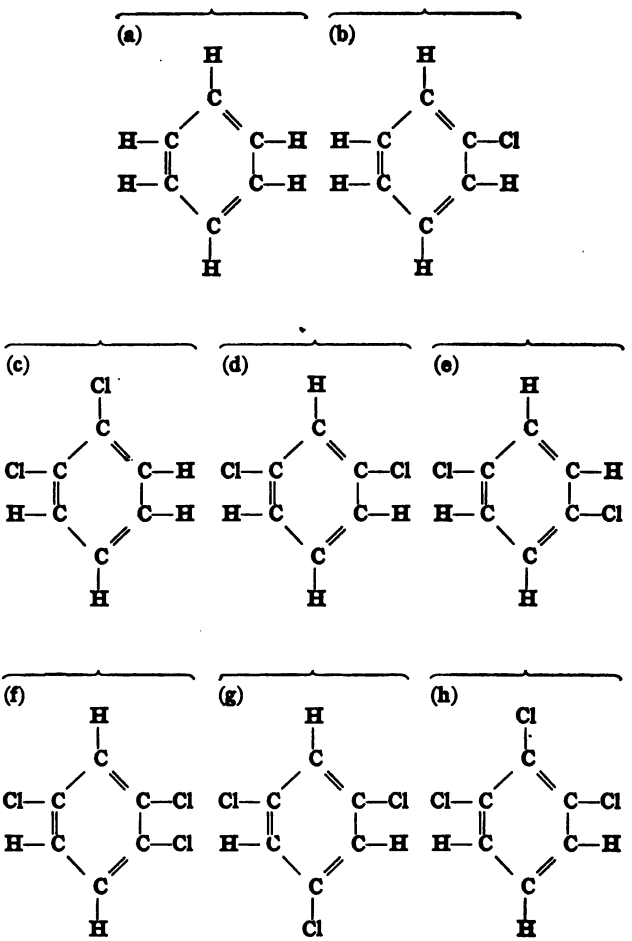


Fig. 13 a
See Fig. 13 b

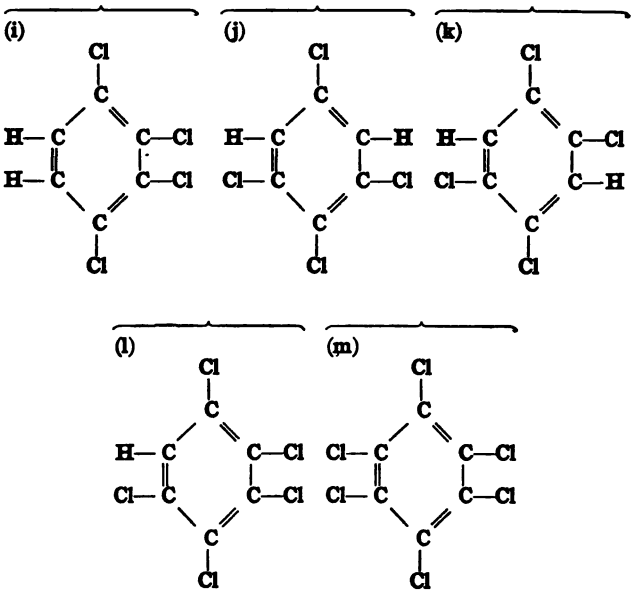


Fig. 13 b

BENZENE AND ITS CHLORINE DERIVATIVES

The significance of these formulæ is explained in the text.

would be known to the chemist as a "chlorine derivative of benzene."

Now a moment's study will show that by a simple examination of the ring formula we can predict the number of such derivatives which we shall be able to form, provided the formula is correct. If only one hydrogen atom is replaced there is only one possible compound, (b) Figure 13, since the ring is perfectly symmetrical and hence the structure which is formed is the same no matter which hydrogen atom is disturbed. However, if two, three, or

four hydrogen atoms are replaced there will be three different molecular structures corresponding to each of these numbers. This fact is shown in Figure 13 (c) to (k) inclusive. No more than three can be formed, however, in each case. If five or six chlorine atoms are introduced only one compound can be produced corresponding to each number, (l) and (m), respectively, in the Figure. We are thus able to prophesy the possibility of twelve chlorine derivatives of benzene and of no more than twelve. The actual study of this substance in the laboratory has revealed the existence of all of these derivatives and has proven the impossibility of producing any others. This is a striking verification of the idea that the benzene molecule actually has a ring structure.

We have studied this matter of the structure of the molecule in connection with benzene because the formula of this substance is distinctive and is one of the most successful in its applications. However, there are other instances of the same thing which are almost equally striking. Indeed the science of organic chemistry would be practically impossible without the help which is provided by a knowledge of the actual structure of the molecules composing the substances with which it deals. The exact structure of the molecule is of less importance in inorganic chemistry because here the molecules are so much simpler.

Molecules of Single Elements. — In this connection it may be well to note the fact that the atoms of the *elements* in the pure state generally unite to form molecules, which are thus made up of two or more atoms of the same kind. Thus hydrogen gas is not composed of free atoms but of *hydrogen molecules*, each of which contains two atoms of the element. Many simple elements in gaseous form have two atoms in their molecules. The vapor of the

metal mercury is distinguished from most elementary gases by the fact that its atoms are uncombined. Some elements, on the other hand, form molecules containing as many as seven similar atoms, and the same element may yield molecules of different sizes under different condi-

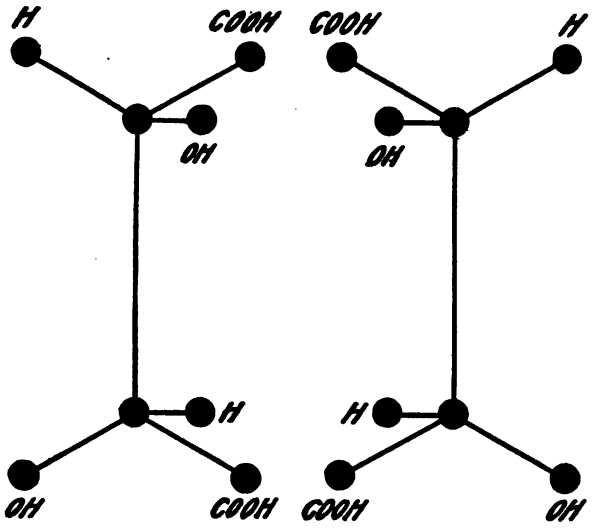


Fig. 14

MODELS OF TARTARIC ACID MOLECULES

To gain a correct impression from this drawing one should imagine the H and OH circles on the inner portion of each model to be spheres projecting outward from the page, so that the models have a three-dimensional form. The letters attached to each black circle stand for the groups of atoms which the circle represents, and the lines connecting the circles indicate the structure of the molecules. It will be observed that these two molecules, which are of "right" and "left" tartaric acid respectively, are so constructed that one is the mirror-image of the other. This relationship of structure is offered as an explanation of the similar relationship which exists between the structure of the crystals shown in Figure 15.

tions. The various forms of pure sulphur and of phosphorus—the yellow and the red—probably correspond to molecules containing different numbers of atoms of these elements. It is possible that the three familiar

forms of the element carbon: charcoal, graphite, and diamond, may be due to the same causes.

Molecular and Crystal Structure. — The structure of the molecule which is characteristic of a substance is probably closely related with the shape of the crystals which it produces.[1] Nearly all pure substances will take on a characteristic crystalline shape under the right conditions. There are certain pairs of sugars — compounds of

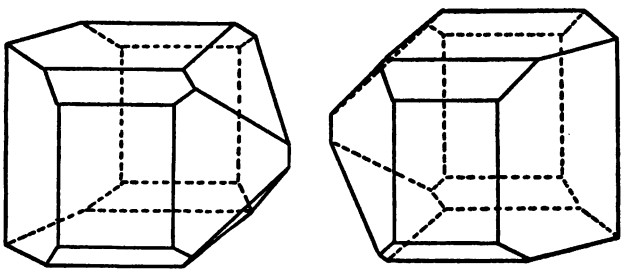


Fig. 15

CRYSTALS OF "RIGHT" AND "LEFT" TARTARIC ACIDS

It will be observed that the two crystals represented above are identical in form except for the fact that one is the mirror-image of the other; what is on the right-hand side of one is on the left-hand side of the other. The two crystalline forms represent two different kinds of tartaric acid, but ordinary chemical analysis reveals no difference in their composition. It is supposed that the actual basis of the distinction lies in the fact that the molecules of the two acids differ in the same general way in which the crystals differ. These molecules are symbolized in Figure 14.

carbon, hydrogen, and oxygen — the molecules of which as represented in their structural formulæ, are distinguished from each other only by the fact that one is the mirror-image of the other. This difference is made clear in the accompanying Figure 14. Now it turns out that when these sugars crystallize, although the crystals do not have the same form as the molecules, *they do differ*

[1] Present-day studies of crystal constitution (see Section 22) show that the atom and not primarily the molecule is the unit of structure.

in the same way in which the molecules differ, *i.e.*, one is the mirror-image of the other. This fact, which is shown by a comparison of Figures 14 and 15, seems to prove quite conclusively that the shape of the crystal depends directly upon that of the molecule.

In this connection it is interesting to note that whereas one of these sugars — either in the crystalline form or in solution — turns polarized light to the left, the other turns it to the right, and in exactly the same proportion. This fact speaks for the truth of the formulæ which have been assigned to the compounds.

Further considerations with regard to crystal structure will be found in Section 22.

REFERENCES

An excellent, detailed and not very difficult discussion of "The Constitution of the Molecule," will be found in W. Nernst's "Theoretical Chemistry," English translation from 6th German edition (1911), Book II, Chapter 4, pp. 278–300.

Simpler considerations appear in F. J. Moore's "Outline of Organic Chemistry" (1910). Chapter VIII, pp. 147–161, deals with the phenomena of crystal form above mentioned.

Section 8

THE PHYSICAL PROPERTIES OF COMPOUND SUBSTANCES

Importance of the Internal Molecular Forces. — We have asserted in Section 7, above, that the properties of compound substances depend principally upon the manner in which the atoms are arranged in the molecule. Strictly speaking, however, we must say that the characteristic properties of a substance depend upon the strength and arrangement of the *forces* of attraction which hold the molecule together. We perceive such qualities of bodies as hardness, elasticity, color, odor, etc., only

because these bodies bring to bear upon our organs of touch, sight, and smell certain characteristic combinations of forces. The nature of these forces must always depend at least in part upon the nature of the forces within and between the molecules of which the body is made up.

Hard bodies are those in which the forces which exist between the molecules are very strong and hold them closely together, so that the body cannot be distorted by our touch. An elastic body is one in which the same forces act to restore its original shape, once it has been distorted. Among other characteristic properties of compound substances which must be determined by the internal and external forces of the molecule may be mentioned their melting and freezing points, their latent heats of vaporization and of fusion, their dielectric constants (or the degree to which they alter the intensity of an electrical field in which they are placed), their optical nature, their surface tension and the pressure exerted by their vapor when in the liquid state, their chemical activity, the forms of their crystals, their compressibility, viscosity, magnetic power, etc. In the course of the discussion in both Part I and II, the manner in which these properties are determined by molecular and inter-molecular forces will gradually be made clear.

Color. — The *colors* of substances depend upon the nature of the light which they absorb and reflect. If a body looks red in white light this means that it absorbs a great deal of green and blue light and reflects a relatively large amount of red. This power to absorb one light and to reflect another is known to depend directly upon the strength of the forces which hold the electrons in the molecule, as is explained in Section 41, below.

The nature of the elements of which compounds are made up is undoubtedly of the utmost importance in

determining their properties, but it is probable that the elementary atoms are effective primarily through their power to regulate the forces within the compound molecules. Thus the blue color of many copper compounds is due to the copper atom common to all. But since this color changes to red or brown when certain well-known changes occur in the forces binding the molecules of such compounds together, we are compelled again to conclude that what may be called the "dynamical (or force) constitution of the molecule" is the immediate cause of the physical properties of the corresponding substance.

Allotropism. — The marked differences which exist between the so-called "allotropic" forms of certain elements (such as carbon; see Section 7) obviously cannot be attributed to differences in the elementary constitution of the substances, and hence must be explained in terms of the different arrangement, and degree of exhaustion, of the same atomic *forces*. Diamond — which is one of the hardest substances known — is made up of exactly the same element as charcoal and graphite, which are relatively soft.

The Mystery of Chemical Change. — Accordingly, reflection should free us of the mystery which usually attaches to the qualitative modifications of the properties of bodies which occur in chemical changes. Molecules are not merely chance "heaps" of different atoms. They are definite and relatively stable individuals, the natures of which depend, of course, upon the forces latent in the atoms which make them up, but which nevertheless realize in their own constitution "force patterns" which do not exist elsewhere. Each new atomic compound means a new system of such forces, and consequently a new substance, possessing an individuality of its own.

Recent developments connected with the study of isotopism (see Section 6), make it very probable that the principal physical and chemical properties of elementary substances depend directly only upon the number and arrangement of the electrons in the outer shell of an atom. This superficial structure is identical in isotopes, although the inner, nuclear formations differ. Now, there is little doubt that it is the outer or "valency" electrons (Cf. Section 34), which are active, and change their positions, in chemical reactions. Consequently, it is natural, if what has just been said is true, that the properties of compounds should differ radically from those of the elements which go to make them up. Only a relatively small portion of a complex atom is involved in its everyday dealings with the external world. The immediately interesting things about an atom, so to say, are all superficial, and are easily modified through intercourse with other atoms. From the point of view of chemistry, it is possible that the atom may be more radically altered in a chemical reaction than in a radio-active transformation, although the latter is fundamental and irrevocable, and the former easily reversible.

REFERENCES

The details involved in the above discussion will be further considered in subsequent sections in which references will be given to the special topics concerned.

For a more detailed general discussion see W. Nernst's "Theoretical Chemistry" (1911), Book II, Chapter 5, pp. 303–347, and Norman Campbell's "Modern Electrical Theory," second edition (1913), Chapter XII.

A good discussion of color appears in Franklin and MacNutt's "Light and Sound" (1909), Chapter X. See also M. Luckiesh's excellent volume, "Color and its Applications" (1915).

Section 9

CONCERNING CHEMICAL EQUATIONS

The chemist is accustomed to represent chemical changes by means of *equations*, such as the following:

$$H_2O = 2\,H + O,$$

which is intended to show how water breaks down into hydrogen and oxygen. The symbols on the left-hand side of the equation represent the substances entering into the reaction, and those on the right-hand side represent its products. The equation above, stands for a chemical change of a purely *destructive* type. If the direction of the change is reversed, we have:

$$2\,H + O = H_2O$$

which is a *constructive* reaction. However, very few chemical changes are purely destructive or purely constructive. As a rule, there is simultaneous building up and breaking down. Thus the actual process which occurs when water is decomposed into hydrogen and oxygen is not so simple as we have represented it in the first equation above, but is more accurately symbolized by the following relationship:

$$2\,H_2O = 2H_2 + O_2$$

This reaction probably goes on in two stages, the first being that indicated in the equation which was originally given, and the second being the combination of the free hydrogen and oxygen atoms thus produced, to form the hydrogen and oxygen molecules, H_2 and O_2, respectively, which we mentioned in Section 7. However, since the chemist is usually interested in the so-called "end products" of a reaction, and since in any case the two lines

of change are continuous with each other, the reaction is ordinarily written as shown above.

Section 10

THE FORCES OF ATTRACTION WITHIN BODIES

Everybody is aware of the fact that particles of matter attract each other with a force which is greater the nearer the particles are together. As everyone knows, it is the gravitational attraction between the earth and the bodies upon it which causes the latter to have "weight." Now since all bodies are made up of atoms it follows that the forces of gravity must depend in some way upon attractions which atoms exert upon each other, and on account of the fact that the atoms are separated, at least in the case of solids and liquids, by very minute distances we should expect these "inter-atomic" forces to be relatively more powerful than are those of ordinary gravitation. But as far as the atoms are concerned gravitation is only a sample of much more powerful forces, for the former is in all probability a mere *residue* from the latter.

At the present time the nature of the relationship which almost certainly exists between gravitation and the mutual attractions of the atoms is largely a mystery, but strange as it may seem, we are much clearer concerning the connection between atomic and molecular attractions, between "chemical affinity" and the forces of cohesion within bodies.

As we have suggested in Section 6, the atoms are probably complex, being made up of ultimate particles which are much smaller than the atoms themselves. On account of the great stability of atoms we must suppose these particles to be held in position by very powerful forces of attraction. These forces, which are probably

electrical, are not perfectly balanced within the atoms and hence tend to be effective in causing them to adhere to each other. Such secondary attraction is probably the basis of what is commonly called "chemical affinity," the force which binds atoms together into molecules. But just as the tendencies of attraction are not wholly exhausted within the atom, so there are residual attractions which remain after the molecule has been formed, and it is these secondary residual forces which underlie the properties of cohesion, elasticity, and rigidity in solids or liquids. Their existence also accounts for certain striking characteristics of gases, as well as of solids and liquids, as we shall see later on in our discussion.

It is important that the reader should bear in mind the qualitative identity of these different forces of attraction which operate between the particles of which all bodies are composed, and also the nature of their quantitative relationships.

REFERENCES

On the relation between atomic, chemical and cohesion forces, see Sir Oliver Lodge's book on "Electrons" (1906), Chapter XVI.

Also Norman Campbell's "Modern Electrical Theory," second edition (1913), Chapters XII and XIII.

Section 11

"THE KINETIC MOLECULAR THEORY"

The Nature and Foundations of the Theory. — The "proof" of the doctrine that the atoms of all bodies are in constant motion has been given by the so-called "kinetic molecular theory," in connection with the results of experiment. This theory may well be described as an application of the laws of mechanics, or "dynamics," to the world of molecules. The fundamental principles

Plate II

CAVENDISH GRAVITATION APPARATUS

This is a photograph of an extremely delicate instrument employed to demonstrate and measure that most fundamental of all of the dynamic properties of matter, gravitation. The perpendicular tube encloses a fine fiber which suspends the small dumb-bell shaped bar, with its two small silver balls, shown in the middle of the picture. The attraction of the large lead spheres tends to twist this arrangement, which is really a torsion balance, and from the extent of this action it is possible to calculate the magnitude of the gravitational force. This force is exceedingly minute.

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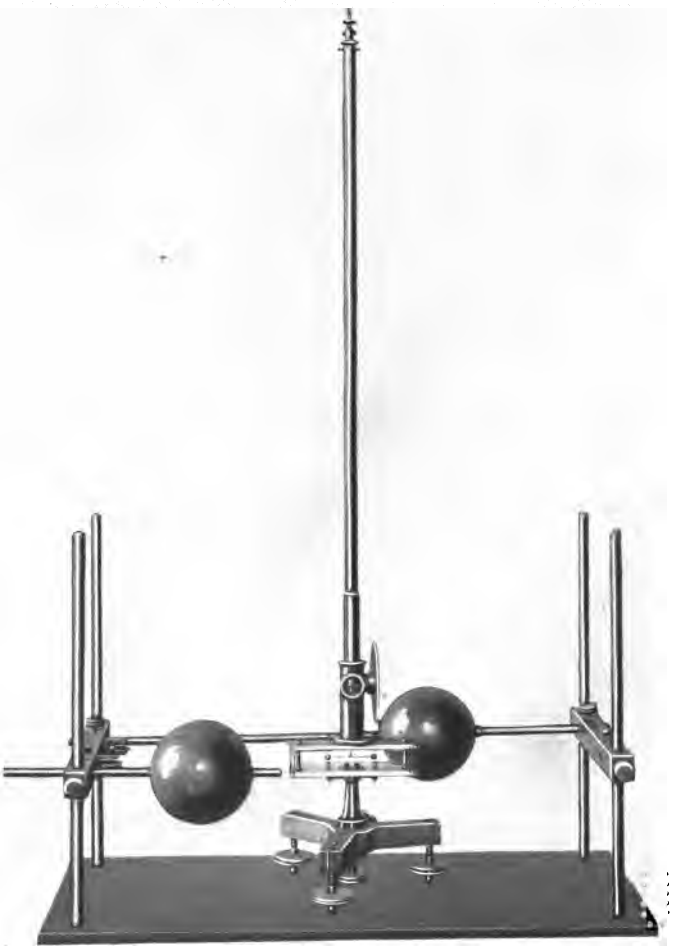


of mechanics are the familiar "laws of motion" of Newton, and it is a very significant fact that these principles which were first applied successfully to astronomical bodies should apply also to the almost infinitely smaller bodies called molecules. Certain very recent considerations tend to limit the applicability of these laws (see Section 54, below), but they certainly apply approximately, and on the average, to a wide variety of molecular happenings.

The kinetic theory regards each molecule as an independent being, endowed with motion and having certain attractions for all other molecules. It then proceeds to investigate the effects which should follow from the presence of a very large number of such molecules in a limited space, making use only of the laws of motion, of geometry, and of arithmetic.

Molecular Chances, and Averages. — It was shown by Maxwell, who may be considered the founder of the kinetic theory, that most of the laws which govern such a mêlée of vibrating particles must be "statistical" in character, that is, that they must depend upon the *average* of a large number of different individual molecular effects. Because of the vast number of molecules which are contained in even a small volume of material substance, these averages are very certain. When a small number of molecules are considered, however, their action proves to be less certain.

The modern theory of matter has thus given rise to a branch of inquiry which is often called "statistical mechanics," because it applies the principles of statistical investigation to mechanical problems. These principles are essentially those of "chance" or "probability." We can tell what will happen in the molecular world in about the same way in which we can predict the events

which occur in human society, although generally with greater accuracy. It is possible for insurance men to calculate with sufficient accuracy for successful business administration, the number of people who will commit suicide or arson during a given period, or who will be killed in train wrecks or in automobile accidents. With regard to one person nothing definite could in general be foretold, but the greater the number of individuals considered, the more precisely are predictions fulfilled. It is the same in the molecular world, and here the number of individuals involved is vast almost beyond conception, so that statistical prophecies are very reliable. However, what may be called the "individuality of molecular activities" is of great importance in modern physics.

The "proof" of the hypothesis of molecular motion to which we have alluded lies in the remarkable correspondence which exists between the results of the kinetic theory and the facts of nature as determined by experiment, a correspondence which applies both to the statistical and to the individual behavior of the molecules.

REFERENCES

On the kinetic theory, see W. P. Boynton's "Application of the Kinetic Theory to Gases, Vapors, Pure Liquids, and the Theory of Solutions," 1904.

Also W. Nernst's "Theoretical Chemistry" (1911), Book II, Chapter II, pp. 197–249. The latter account is perhaps the simpler of the two, and also the more empirical.

Section 12

THE SPEEDS OF MOLECULAR MOTION

The Molecular Counterpart of "Temperature."—The exact temperature of bodies is not directly proportional to the *speed* at which their molecules move, but rather depends upon the average *energy* of molecular motion.

It is a familiar fact that the energy, or "kinetic energy," of a moving body depends not only upon the speed at which it is travelling but also upon its weight or "mass," or — if we consider only bodies made up of the same substance — upon its size. Other things being equal, the larger a body is the more work must be done to set it in motion or to stop it, once it is moving. It is found by calculation from the laws of motion and by experiment, that the energy of motion, or kinetic energy, of any body is proportional to its mass and to the "square" of its velocity.

This measure of energy of motion applies to molecules as well as to visible bodies, and so we must say that if the temperature of a piece of matter is proportional to the average, kinetic energy of its molecules its temperature is proportional to the average square of the speed of these molecules, so that as their speed increases the corresponding temperature increases much more rapidly in proportion. From these considerations, also, it follows that if we have a number of substances at the same temperature the speeds of their respective molecules will on the average, be less the larger (more massive) these molecules are. This must follow because at the same temperature the average energy must be the same regardless of the weight of the molecules, and this can only be true if the heavier molecules are moving at lower speeds than are the others.

When a large number of atoms or molecules of different species and weights are mixed together the average energy of each species will be the same as that of any other species. It seems reasonable that this should be the case, for if the average energies were not equal in this way, the different substances making up the mixture would be at different temperatures, which is incon-

sistent with the well-known fact that all bodies which are in close contact tend to come to the same temperature. As we shall see later (Section 21), even when the vibrating particles are so large as to be visible under the microscope, their average energy of motion is approximately the same as that of the very much smaller molecules. This is one aspect of what is known as the *principle of "the equipartition of energy."*

Actual Molecular Speeds. — We have seen in our previous discussion that atoms and molecules differ widely in weight, and since weight and mass are proportional, it follows from what has been said above about the equality of molecular energies of different substances at the same temperature, that the speeds of different molecules and atoms under these conditions will differ a great deal. The average speed of a hydrogen gas molecule at a temperature corresponding with the freezing point of water is about one and one-eighth miles a second, that of the mercury vapor molecule at the same temperature is about one-tenth of this, or about six hundred feet a second. The mercury molecule weighs just one hundred times as much as the hydrogen molecule. For the same temperature, molecular speeds vary as the square-roots of the molecular masses. Even the mercury molecule moves at the tremendous speed of four hundred miles an hour. Vast as this may seem, it is as nothing compared with the speeds which are attained by molecules and especially by electrons under other conditions which we are to consider at another point in our discussion (see Section 25, below).

The reader should bear in mind the fact that it is the *average* energy of motion which is constant at a given temperature. The speeds of the individual molecules differ enormously, but the variations in one direction

balance those in the other so that from the statistical point of view which we have explained in Section 11 there is constancy.

REFERENCES

For a detailed and simple account of the relations of molecular speeds in the kinetic theory see Chapter III of Part I of O. E. Meyer's "The Kinetic Theory of Gases." A list of concrete values for the speeds of molecules of thirty-one different substances is given on pages 57–58 of the English translation of this work (1899). "Molecular and Atomic Energies" are discussed in Chapter V of Part I.

A still simpler discussion will be found in O. D. Risteen's "Molecules and the Molecular Theory of Matter" (1895), Chapter II.

Section 13

AVERAGE DISTANCE TRAVERSED BY A GAS MOLECULE BETWEEN IMPACTS

The "Mean Free Path."—Since the molecules of a gas are moving helter-skelter it cannot be expected that the distance passed over by individual molecules between "bounces" will always be the same. However, from what we have said in Section 11 about the "statistical" nature of the happenings in the molecular world it might be anticipated that *on the average* this distance would be constant for the same gas under the same conditions. This turns out to be the case, and the distance in question is known in the kinetic theory as the "mean (or average) free path" of the molecule.

The mean free path of a gas molecule under standard conditions is a very important characteristic of the gas on account of the fact that upon its magnitude depend many of the obvious properties of the gas in question. It is clear that, other things being equal, this distance will be greater the smaller the moving molecules and the fewer

there are of them in a given volume. In other words the average uninterrupted motion of the molecules is greater the smaller their chances of collision. When the gas is compressed the mean free path is diminished, so that it varies in a direction opposed to that of the change in pressure.

Properties Depending on "Mean Free Path." — Among other measurable properties of gases which depend upon the magnitude of the mean free path of their molecules are to be mentioned their natural rates of "diffusion" (see Section 14) and the ease with which they conduct electricity. Any phenomenon which depends upon the rate at which individual molecules can move from one point to another in the gas body will also depend upon the size of the "mean free path." Electricity is conducted through gases by being carried along bodily on electrons or molecules which move under the influence of the electrical forces exerted by the dynamo or battery. The longer the mean free path, that is the fewer the obstacles which oppose the motion of the electrified molecules, the less the "resistance" which is offered to the passage of the current. This explains why it is that gases under low pressure — such as exist in many so-called "vacuum-tubes" — conduct electricity so much better than do the same gases at "atmospheric pressure."

For atmospheric gases under ordinary conditions the mean free path is about one one-millionth of an inch in length. In vacuum tubes for the same gases it may be greater than one ten-thousandth of an inch. These magnitudes may seem very small, but when we consider the fact that the average gas molecule is only one three-hundred-millionth of an inch in diameter we see that the free movements of the molecules may be relatively large. The mean free path in hydrogen gas is greater

under the same conditions than that in, say, mercury vapor, for the reason that the molecules of the latter gas are larger than those of the former. Although the length of the mean free path varies inversely as the square of the diameter of the molecules the difference is not very great, owing to the relatively small difference in diameter of the two species of molecules.

On account of the great speed of molecular motion, the time intervals between the successive impacts of gas molecules are very minute even in highly rarefied gases.

REFERENCES

Concerning "Molecular Free Paths and the Phenomena Conditioned by Them" consult Part II of Meyer's "The Kinetic Theory of Gases" (1899).

Section 14

DIFFUSION

One very commonly observed phenomenon which can be accounted for only in terms of the motion of molecules is that of *diffusion*. The nature of this process is best illustrated by the manner in which odors travel. When a bottle of some pungent liquid is uncorked in one corner of an apartment the molecules of the vapor, which is always present above any liquid, swarm out of the bottle and ultimately spread themselves like insects to all parts of the room. Certain of them strike the sensitive surface of the nostrils and produce distinctive sensations of smell. Of course this motion of odoriferous molecules is assisted by the presence of air currents, but these become effective only when diffusion is also possible.

The motion of the molecules in diffusion can seldom resemble a "bee line," since no molecule can be expected to travel across the average room without en-

countering countless others in its course. Diffusion movements must, therefore, have "jagged" paths,

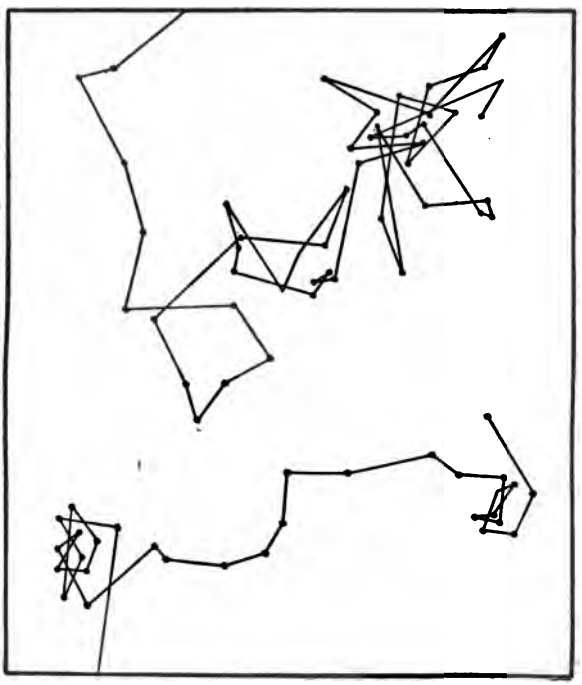


Fig. 16

DIFFUSION PATHS

These jagged lines are supposed to be the paths of two gas molecules which are followed for a short period of time. They show quite clearly what is meant by saying that the motion of such molecules is haphazard, but, although the paths are very far from "bee lines," they nevertheless represent a progressive displacement of the molecules from their original positions. It is in this manner that gases diffuse. The paths represented above were of course not obtained by the observation of gas molecules, but they come from a closely related source, *viz.*, the measurements of M. Perrin of the so-called Brownian movement of small particles suspended in liquids seen under the microscope. As explained in the text the Brownian movement follows the same laws as that of molecules in a gas.

somewhat like that of a flash of lightning (see Figure 16). On account of the tremendous obstacles which

are opposed to the straightforward motion of the molecules, the diffusion of large quantities of a gas or vapor requires long periods of time.

Diffusion would not occur at all if it were not for the heat motion of the molecules.

REFERENCES

On diffusion see Meyer's work already referred to, Chapter III of Part II.

An account of the physical phenomena of diffusion will be found in A. L. Kimball's "The Physical Properties of Gases" (1890), Chapter VI.

Section 15

SOUND

From the modern point of view sound must be regarded as a molecular phenomenon.

Sound is commonly considered to be a species of wave-motion which is set up in the air, or other material substance, by the vibratory motion of the object which is "emitting the sound." Suppose, for example, that a tuning fork is struck. The prongs of the fork are set into rapid vibration and at each of their excursions they push violently against the air molecules which surround them. These molecules are thus thrust away from the fork and communicate their motion to outlying molecules which act in turn upon a third layer of molecules further still from the fork. When the molecules near the fork have conveyed the impulse to the outlying molecules they rebound, just as does a moving billiard-ball which encounters a stationary one under the right conditions.

It can be seen that an impulse of this sort will travel out from the source just as a wave of motion passes along a row of standing dominoes, the first of which has been overturned. The gas molecules, however, unlike the

dominoes, return to their original positions when the wave or impulse has passed, and hence are ready for the generation of a second wave, which is occasioned by the second excursion of the prong of the tuning-fork. The result is that a series of "rarefactions and condensations" among the molecules travel out from the tuning-fork and when these impinge upon the ear they cause the sensation of sound.

When the prong of the tuning-fork sets the air molecules in motion it of course endows them with some of its energy, and it is this energy which is responsible for the stimulation of the ear. The radiation of heat energy from a hot body is different from the radiation of sound energy in several ways. In the first place heat energy may be lost by two distinct processes. A hot body may lose heat energy on account of the fact that the motions of its surface molecules set up similar motions in the molecules of surrounding bodies, or it may lose energy by the generation of "heat waves." These constitute true "radiant heat" and do not consist in the motion of molecules, as do sound waves, but rather are closely similar to light, that is electromagnetic waves.

REFERENCES

An excellent semi-popular work "On Sound," although now an old one, is John Tyndal's book of that name (1888). The first Chapter is especially pertinent. See also Franklin & MacNutt's "Light and Sound" (1909).

Section 16

LATENT HEATS

It is a well-known fact that when a solid melts, and that when a liquid is vaporized, definite amounts of heat energy are absorbed, the so-called *latent heats of fusion and of vaporization.* The cause of this absorption of en-

ergy can be explained in a general way by the molecular theory.

The Latent Heat of Fusion. — We have said that the molecules of a true solid body are unable to alter their relative positions and hence vibrate ceaselessly about the same centers. In the light of recent studies of the structure of crystals, it seems probable that the molecules of a solid are also not free to *rotate*, and that in a single crystalline unit they all point in the same general direction. This fixity of the molecules is what gives the solid its rigidity, and we must suppose it to be due to the existence of definite forces of attraction existing between them.

Any addition to the heat of a body occurs in opposition to these affinities. Melting occurs when the energy of motion acquired by the molecules is sufficient to enable them to break away from the chains of attraction which bind them to their neighbors. When this happens, however, the attraction necessarily reduces the initial speeds of the molecules, because they constantly tend to be dragged back to their original positions. Since heat consists in the energy of molecular motion, this slowing down of the molecules as they escape from their neighbors must mean the disappearance or "absorption" of a certain amount of heat, and this is the *latent heat of fusion* which we have mentioned above.

It is obvious that when the temperature of a body is near the melting point only a relatively small force should be required to distort it, since the forces which hold the molecules in their places are very much weakened. This consideration explains the increased "malleability" and plasticity which is exhibited by many bodies at high temperatures.

When a liquid cools, the forces of attraction again

come into play and as the molecules drop into their positions these forces increase the velocity of their motion, so that the latent heat once more appears in active form.

Surface Tension.—The molecules of a *liquid* are free to move anywhere within the liquid but are, for the most part, held within its bounds by a force which may be appropriately designated as the "attraction of the mass." The fact that an attraction of this character exists is proven by the phenomenon of *surface tension.* All liquids behave as if they were surrounded by a very thin and tightly stretched skin, an effect which is due to the strong attraction exerted upon the surface molecules by those which are underneath.

The Latent Heat of Vaporization. — The evaporation of a liquid consists in the escape of certain of its molecules through this surface film. In order to escape in this way they must move at a velocity sufficient to enable them to overcome the inwardly directed force which exists at the surface. This means that, in general, only the fastest moving molecules can gain their freedom, and even they achieve it at a certain price, namely a reduction of their speed.

The action whereby the fastest moving molecules are constantly being removed from the liquid together with this reduction of speed necessarily involves a loss of heat energy. This loss or absorption of heat is called the *latent heat of vaporization.* Everyone is familiar with the truth that the evaporation of a liquid has a cooling effect, and this effect is to be attributed to the fact that evaporation involves the absorption of heat energy.

When a vapor molecule returns to the liquid from which it sprang, its speed is increased as it passes through the surface. In this way the latent heat of vaporization is reconverted into energy of molecular motion.

REFERENCES

Concerning latent heats consult H. C. Jones' "The Elements of Physical Chemistry" (1902), pp. 104–106, 161–162, which, however, does not deal with the molecular explanation of the phenomena. This is discussed, mathematically, in W. Nernst's "Theoretical Chemistry" (1911), pp. 236–238. An elaborate discussion of surface tension phenomena will be found in the eleventh edition of the Encyclopaedia Britannica under "Capillarity."

Section 17

"CRITICAL" AND BOILING POINTS OF LIQUIDS

As the temperature of a liquid is increased, a point is finally reached at which the influences of separation due to the movement of its molecules just balance the forces of inter-molecular attraction. This is called the "critical point" of the liquid.

Since the film of surface tension which surrounds a liquid is due to the activity of its internal forces of attraction, this film vanishes at the critical point, thus obliterating the distinction between the liquid and its vapor. Just below the critical point the latent heat of vaporization is practically zero, on account of the absence of any effective forces of attraction to be overcome in separating the molecules. Both the surface tension and the latent heat of vaporization decrease gradually as the temperature rises.

Under ordinary conditions the majority of liquids *boil* at temperatures which are far below their critical points.

Since the atmosphere above a liquid exerts a confining pressure upon it, it is impossible for vapor to form *within* the mass of the liquid until the pressure exerted by the vapor itself is greater than that of the atmosphere. When this point has been reached the production of vapor *within* the body of the liquid results in the formation of

bubbles which rise to the surface and break, the familiar phenomenon of boiling. In accordance with this explanation it is easy to see why the boiling points of all liquids should be lowered by a decrease in the pressure of the surrounding atmosphere, and raised by an increase in the pressure.

REFERENCES

On critical and boiling points see A. D. Risteen's "Molecules and the Molecular Theory of Matter" (1895), pp. 80–84.
Also Nernst's "Theoretical Chemistry" (1911), pp. 63–67.

Section 18

THE SIMPLE LAWS OF GASES AND OF SOLUTIONS

Boyle's Law. — The relations which exist between the pressure which is exerted by a gas, its temperature, and its state of compression, *i.e.*, its density, are very simple, and are at once accounted for by the molecular theory. The pressure acting upon a vessel which contains a gas must obviously become greater when the size of the vessel is decreased, because although the number of molecules remains constant, the frequency with which they strike the sides of the vessel must increase. This is the basis of the well-known *law of Boyle*, which states that the pressure exerted by a given quantity of gas is inversely proportional to the volume which it occupies. The law can in fact be derived mathematically by considering the action of the moving molecules.

Charles' Law. — When the temperature of a gas increases, the molecules move faster, and hence the pressure must increase also. It can be shown by a simple calculation that the pressure caused by the bombardment of the sides of the vessel by the flying molecules should be proportional to the *average energy* of this motion. This

means that the pressure of a gas is directly proportional to its temperature measured in degrees above the "absolute zero": the *law of Charles.*

"*Absolute Zero.*" — "Absolute zero" is defined as a point of temperature at which the molecules are motionless and hence as a point at which the gas-pressure is also zero. By measurements upon gases we can find out how much their pressures decrease for each unit of temperature, and if we then divide their pressure at any temperature by this amount, we shall learn the number of degrees which must be subtracted from the temperature in question in order to give us the absolute zero. This is the *principle of Gay-Lussac.* As should be expected, it turns out that the change in pressure for a given change in temperature is approximately the same proportion of the total pressure for all gases studied under the same conditions.

The Principle of Avogadro. — In Section 12 we have discussed the principle according to which all species of molecules at the same temperature have the same average energy of motion, regardless of their other characteristics. If this principle is valid the pressure exerted by a given body of gas should be independent of the kind of molecules of which it is made up, and should depend, as we have stated above, merely upon the *number* of molecules of any sort whatever which are present. From this it follows that if the same vessel is filled successively with different kinds of gas at the same temperature and pressure, the same number of molecules will be present in each case, or in other words: "equal volumes of all gases under the same conditions of temperature and pressure contain equal numbers of molecules," — which is the famous *principle of Avogadro.*

As we have already seen (Section 5, above), it follows

from Avogadro's rule that equal volumes of similarly conditioned gases should have weights which are in the same proportion as the weights of their respective molecules. This is another consideration which affects the form of the so-called "gas law," a familiar formula which summarizes the relationships which we are now discussing.

The Formula of van der Waals. — It has been shown by experiment that the law of Boyle does not hold for high pressures and low temperatures. The reason for this we have already mentioned in Section 2. It is to be found in the fact that Boyle's law is calculated on the assumption that the molecules are geometrical points, whereas in reality they have a volume of their own, a fact which must affect the ease with which the gas is compressed. Moreover the gas molecules exert an attraction upon each other which tends to make compression easier at high than at low pressures. The influence of these factors has been summed up in the very accurate *gas formula of van der Waals.*

As pointed out in Section 19, below, the above considerations apply, at least approximately, to substances in the dissolved, as well as in the gaseous state.

REFERENCES

Concerning the laws of gases consult A. D. Risteen's "Molecules and the Molecular Theory," pp. 40–58; W. Nernst's "Theoretical Chemistry" (1911), pp. 198–201, or G. Senter's "Outline of Physical Chemistry" (1908), Chapter II.

Section 19

OSMOTIC PRESSURE

When a substance, such as sugar, is dissolved in (say) water, its molecules are separated from each other and wander about among the water molecules. If we neglect

the presence of the latter we may regard the state of the sugar as essentially that of a gas having a density corresponding to the concentration of the sugar in the water.

Now there is an arrangement by means of which it can be shown that a dissolved substance actually does behave like a gas. Suppose that some sugar solution is placed in a balloon made of a membrane through which water can pass without difficulty, but which is impenetrable to the molecules of sugar. If we now place this balloon in a glass of water it will tend to expand and may even burst. This effect is due to the fact that the sugar molecules in the course of their heat vibrations strike the sides of the balloon, and being unable to pass through it as the water molecules do, they tend by their impact to force it outwards.

General considerations lead us to believe that the laws of this so-called "osmotic pressure" should be the same as those of gases, and this is shown by measurements to be approximately the case.

REFERENCES

A popular discussion of the phenomena of osmotic pressure appears in W. C. D. Whetham's "The Recent Development of Physical Science" (1904), pp. 104–124. For more advanced considerations, see H. C. Jones' "The Elements of Physical Chemistry" (1902), pp. 179–199.

Section 20

HEAT CONDUCTION

Evidently, if the molecular theory is true, gases should be better conductors of heat, per unit of mass, than are liquids, since their constituent molecules are more free to change their positions, thus permitting a more rapid mixing of the fast and the slow. For the same reason

liquids should be better conductors than solids. These expectations appear to be borne out by the facts of nature.

There seems to be an exception to the rule, however, in the case of metals, which are the best conductors of heat known. This apparent exception is explained, however, by the fact that metals contain vast numbers of "free electrons," particles so small that they can travel about among the molecules of the metal almost as if they were in unobstructed space. Indeed, the metal may be said to contain negative electricity in gaseous form. These minute particles partake of the heat vibration of the molecules, and by their very rapid motion quickly bring the temperature of all parts of a metallic body to a uniform level. Metals are as good conductors as the lightest gases because the mass of an electron is exceedingly small, even as compared with that of the hydrogen atom, and hence, in accordance with the equipartition principle (see Section 12) must move faster at the same temperature. Besides this, it is probable that electrons can pass through the body of an atom without being stopped.

REFERENCES

On the conduction of heat see Meyer's "The Kinetic Theory of Gases," Part II, Chapter IX (trans. 1899).

Section 21

THE BROWNIAN MOVEMENT AND ITS MEASUREMENT

Perrin's Experiments. — The work upon the physics of the Brownian movement is still new. Credit for the experimental side of the investigation belongs largely to the French scientist Jean Perrin, whose methods of measuring the movements are exceedingly ingenious.

The Brownian particles which were employed by Perrin were produced by the precipitation of alcoholic

solutions of various gums by pouring these solutions into water. They varied in size from about one twenty-five-thousandth to one two-hundred-and-fiftieth of an inch in diameter. Their motions were measured by direct observation under the microscope, and also indirectly by means of certain calculations.

Perrin was able to show that these minute drops of gamboge and other gums, when made into emulsions with water, behave in every way like the molecules of a gas of enormous molecular weight. This applies to such characteristic processes as average speed, rates of diffusion, pressure, etc.

Verification of Equipartition of Energy. — One very interesting outcome of Perrin's work lies in its remarkable verification of the principle that the average energy of vibration of any species of particle depends only on the temperature of the mass of matter considered and not on the weight or size of the particles themselves (Section 12). Some of the particles which he studied were many thousand times as large and heavy as the heaviest known atom, and yet their average energy appeared to be substantially identical with that characteristic of all atoms or molecules at the temperature under observation. He was able to prove, moreover, that the particles have an average energy of *rotation* which is the same as that of their translatory movements, a result in harmony with the demands of theory.

Other investigations have shown that the Brownian movement in *gases* follows the same laws as those which hold among particles suspended in liquids.

REFERENCES

Perrin's own account of his researches on the Brownian movement will be found in "The Brownian Movement and Molecular Reality," translated by F. Soddy (London, 1910). For the most part the book is not difficult reading.

Section 22

THE SOLID AND CRYSTALLINE STATES

The Crystal as a Unit of Structure. — The statement that solid bodies are characterized by an orderly arrangement of their molecules implies that all solids are crystalline. This implication is probably correct in spite of the fact that chemistry distinguishes between crystalline and the so-called "amorphous" solids. Amorphous, or formless, bodies may be regarded as crystalline bodies in which the crystals are very small.[1] Strong reasons exist for believing that this holds even for the so-called "colloidal" substances, which are usually contrasted with "crystalloids."

If this is the true view the arrangement of the molecules in the entire mass cannot be quite orderly, but it is probably permanent. When solids are broken the surfaces of fracture generally coincide with the surfaces of the crystals of which they are composed. It would not be wrong to regard an ordinary solid body as a closely packed mass of smaller bodies, the individual crystals, which alone represent the characteristic form of a solid. The crystal thus becomes the unit of solid matter next in order above the molecule. However, there are some perfectly definite crystals which seem to be decomposable into smaller, similar, crystals without limit. Such a substance, for example, is mica, which crystallizes in sheets, but no matter how thin a sheet of mica may be,

[1] As elsewhere stated, the recently discovered "liquid crystals" introduce a somewhat mysterious element into these considerations. It seems probable that in the last analysis liquid crystals will be found to depend on a somewhat different set of forces than do crystals of solids.

it is always theoretically possible to split it into two thinner sheets, provided, of course, that the first one is not of molecular thinness. It seems to be characteristic of the molecules which compose the mica to arrange themselves in geometrical planes.

Crystal Structure as Studied by X Rays. — Very recently it has been found that X rays, when reflected from a crystal surface, are broken up into a pattern the nature of which varies with the crystal employed. The principle in accordance with which this pattern is formed is well known, — being that of optical diffraction or interference — so that from the character of the pattern it is possible to deduce the arrangement of the molecules within the crystal. It appears from these studies, the basis of which will be further discussed in Section 55, below, that the unit of crystalline structure, — from a geometrical point of view, at least — is not the molecule, but the atom. Crystal form appears to result from an extension of the same architectural principles upon which the molecule is built.

The cubical crystal of potassium chloride, for example, seems to be made up of a rectangular lattice-work of alternate potassium and chlorine atoms, placed at equal distances from one another. It is natural that there should be a close similarity between the external shape of the crystal and that of the spatial configuration of its component atoms, but it is not always possible to infer the latter from the former. For instance, the crystal of potassium bromide, which is externally similar to that of the chloride, appears to have atoms not only at the corners of a simple cubical lattice-work, but also in the centers of all of the cube faces. Sodium chloride, or common salt, another cubical crystal, has an even more complex structure.

Stages Between Solid and Liquid: Liquid Crystals. — Of course all conceivable stages exist between the solid and the liquid states. It would be difficult, for example, to say whether such a substance as asphalt under certain conditions of temperature is a solid or a liquid, and experiments have shown that even very hard and brittle substances like the crystals of common salt exhibit definite evidence of vaporization, a process usually ascribed only to liquids.

Liquid crystals probably depend upon the definite relative arrangement of molecules which may nevertheless alter their absolute position. Just as in the living organism, the actual matter changes as time goes on, although the form remains practically constant. In other words, it is not impossible to conceive a combination of orderly arrangement, such as is demanded by the crystalline state, with relative freedom of translatory movement of the molecules among themselves, which seems to characterize the liquid state. In ideal solids, however, whatever the arrangement, this movement cannot occur, and motion of the molecules must be exclusively vibratory.

It is to be expected that the new X ray method of studying crystalline structure will eventually clear up most of these mysteries, and at the same time throw light upon the very closely related problem of the constitution of the molecule. As yet, only a few simple crystals have been analyzed by this means.

REFERENCES

On the "Molecular Theory of Solids" see Risteen's "Molecules and the Molecular Theory of Matter," Chapter IV.

A German work on liquid crystals is: "Die Neue Welt der Flussigen Kristalle," by O. Lehmann (1911).

On the analysis of crystals by means of X rays, see G. W. C. Kaye's "X rays" (1914), pp. 168–204; and W. H. and W. L. Bragg's "X Rays and Crystal Structure" (1915).

Section 23

VAPOR PRESSURE AND THE LAW OF DISTRIBUTION OF MOLECULAR SPEEDS

The "Distribution Curve" of Molecular Speeds. — In Section 11 it is said that the behavior of molecules can be studied satisfactorily only by the use of the statistical method. Even at a constant temperature all of the molecules do not move at the same speed; it is the average speed which is constant. However, because of the enormous number of molecules which are contained in any body which we may consider, it is possible to make true statistical statements which give us more detailed information about the state of affairs in the body than does the mere knowledge of the average velocity of the molecules.

Some of the molecules of a body move faster than the average and others move more slowly, but on account of the vast number which are present and the consequent great frequency of their collisions there exists a constant levelling tendency, a continuous redistribution of energy, which tends to make them all approximate the average speed. Theoretical considerations show that in a chaos of molecules such as is contemplated by the kinetic theory *there must be far more molecules moving at approximately the average speed than at any other speed,* and that the more the speed of a molecule departs from the average the fewer of its kind there must be. This principle is often spoken of as the "a law of distribution of molecular speeds," and it is of the utmost importance in the study

of heat and allied phenomena. As shown in Figure 17, it is mathematically similar to the well-known "curve of chance" with which the reader may be familiar.

The Laws of "Vapor Pressure." — Evaporation, it has been explained, consists in the escape from the surface

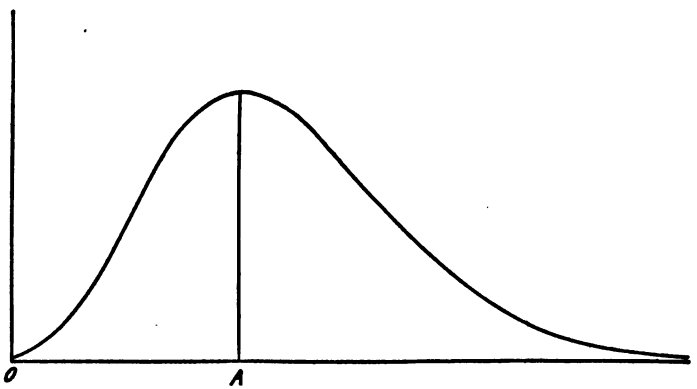


Fig. 17

"DISTRIBUTION CURVE" FOR MOLECULAR SPEEDS

This curve shows geometrically the relative number of molecules moving at speeds which differ more or less from the average speed. Relative speed is measured from left to right along the horizontal line and relative number along the vertical line. *A* is the point corresponding with the "average energy" of all of the molecules. It is evident from the diagram that there are more molecules moving at approximately this speed than at any other, and that the more any (approximate) speed differs from the average the fewer will be the molecules moving at this speed. This curve is a special case of the so-called "curve of error" which represents a law of the utmost importance in modern physics.

of a liquid of certain molecules which move faster than the average. According to the above law of the distribution of molecular velocities, as the temperature of the liquid is increased the number of molecules which escape should increase also, and the exact nature of this increase can be predicted from the law.

The vapor above a liquid is a gas, and hence exerts a

pressure upon the bodies immersed in it. This pressure must follow the ordinary gas laws which we have discussed in Section 18. Since according to these laws the pressure is proportional to the number of molecules present in a given volume, and since this number increases with the temperature of the liquid, the "vapor pressure," as it is called, should increase with the temperature also, and in a way harmonious with the law of distribution of molecular speeds.

Empirical measurements show that the actual rise of the vapor pressure of all liquids is quite closely in accordance with the theoretically deduced law. Everybody is acquainted with the general fact that liquids evaporate faster the hotter they are.

It might at first be thought that the vapor escaping from a liquid would be at a higher temperature than the liquid itself, because only the fast-moving molecules are able to pass through the surface. However, as we have indicated in Section 16, the speeds of all of these molecules are slowed down under the influence of the film of surface tension. It so happens that this decrease, which stands for the absorption of the latent heat of vaporization of the substance, is of exactly the right magnitude to reduce the average speed of the escaping molecules so that the temperature of the vapor is the same as that of the liquid from which it rises. This can be shown theoretically by a consideration of the law of distribution of molecular speeds.

REFERENCES

On the "law of distribution" refer to Meyer's work, Chapter III of Part I (see Note 12).

A mathematical discussion of vaporization will be found in Chapter VII of H. P. Boynton's "Applications of the Kinetic Theory, etc." (1904).

Section 24

HEAT ENERGY AND SPECIFIC HEATS

The total heat energy of any body is the sum of the energies of motion of all of its molecules. It can be estimated approximately by multiplying the average energy of the molecules by the total number of molecules in the body.

When the temperature of a given weight, say one ounce, of a substance is increased one degree, a definite amount of energy has to be added to it in the form of heat. If this amount of energy be divided by the amount required to bring about the same change in an equal weight of water, the quotient is the "specific heat" of the first substance.

Atomic Heats. — Measurements have shown that the specific heats of different substances vary quite widely, but it was discovered by the French investigators, Du Long and Petit, that if the specific heat of any elementary substance in the solid state be multiplied by its *atomic weight*, the resulting product is approximately 6, no matter what element is taken. The reason for this striking fact is not far to seek. It is found in the principle that the average energy of motion of any group of molecules is independent of their species (see Section 12). If all atoms at the same temperature have the same energy of motion, then the energy which must be added to their motion to produce a change in temperature must be independent of their species and hence of the nature of the substance involved. Multiplying the specific heat of an element by the atomic weight reduces the measure of heat capacity to terms of *number* of atoms alone, eliminating the factor of weight.

To raise the temperature of a gas it is only necessary to increase the energy of motion of its molecules, but the molecules of solids and liquids are bound together by strong forces of attraction, and when their vibrations are increased, an amount of energy must be utilized in overcoming these forces which is equal to that which enters into the increased motion. Accordingly, the specific heat of a substance in the solid or liquid form should be about twice that in the gaseous form, and this is found to be the case in nature.

Now the considerations which apply to elementary substances apply also to compounds, although with less accuracy. When the specific heat of a compound is multiplied by its molecular weight, that is by the sum of the weights of its contained atoms, the product does not vary a great deal from 6, if the substance is in the solid form, or 3, if it is in the gaseous form. However, the variations which do occur are sufficient to require explanation, and this must be given in terms of the "force constitution" of the molecule of which we have spoken at some length in Section 8. In general, the stronger the internal forces of the compound the higher will be its specific heat, since a large amount of energy will be absorbed in setting the parts of its molecules into relative vibration, if the attractions which hold these parts together are powerful. It is necessary that the atoms should vibrate within the molecule as well as with the molecule as a whole, and the average energy of this internal vibration should be equal to that of the grosser molecular movement.

It has recently been discovered that the specific heats of all substances decrease very rapidly at very low temperatures, so that at absolute zero they would probably themselves be zero. The exact meaning of this strange

fact is not yet clear, but it seems to be related with the newly suspected atomic nature of radiant, and perhaps all, energy. We shall discuss this matter briefly in Section 54.

REFERENCES

The specific heat of gases is discussed on pp. 63–74, of Jones' "Elements of Physical Chemistry" (1902), liquids on pages 106–110 and that of solids on pp. 162–166.

Consult also James Walker's "Introduction to Physical Chemistry" (1901), Chapter V.

On the changes in specific heats which occur at low temperature, see W. Nernst's "Theoretical Chemistry" (1911), pp. 710–716.

Section 25

THE DISCOVERY AND MEASUREMENT OF THE ELECTRON

Thomson's Determination of the Electronic Mass and Charge. — The electron was discovered by J. J. Thomson as the result of a series of epoch-making and very ingenious experiments. When an electrical discharge passes through a tube from which the air has been partly exhausted it consists, in part, of a beam of rays which seem to be emitted from the negative pole, or "cathode," of the battery or induction coil. (See Figure 18.) Thomson showed that these so-called "cathode rays" are made up of very minute bodies nearly two thousand times lighter than hydrogen atoms, and moving at a speed which varies with conditions but which is in general about one-tenth that of light, or about twenty thousand miles a second.

Thomson did not determine the size of the electron directly but only its weight, or more strictly speaking its mass. This he was able to do by use of the well-known principle that the more massive a body is, and the higher

its velocity, the greater is the resistance which it offers to change in its state of motion. It was found that the cathode rays could be bent by the action of a magnet, a fact which showed them to bear electrical charges, and by measuring the magnitude of this bend as compared with the strength of the magnet employed, a basis was provided for the calculation of the mass of the moving

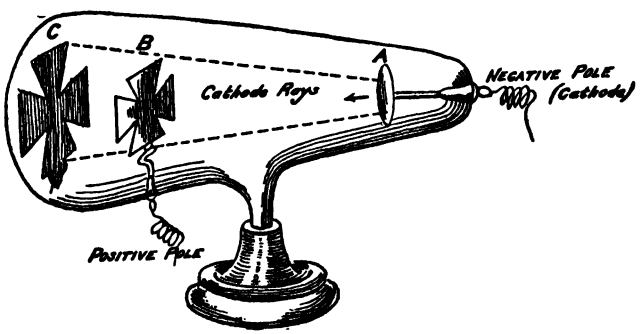


Fig. 18

VACUUM TUBE TO SHOW THE ACTION OF THE CATHODE RAYS

The cathode rays are emitted from the plate *A* and travel away from it in straight lines, a fact which is shown by the character of the shadow, *C*, cast by the metal cross, *B*. This shadow appears in the glow which is produced where the rays strike the end of the tube.

particles. (See Figure 19.) Measurement of the bend of the rays under the influence of magnetism alone did not permit Thomson to separate the effect of the speed at which the particles were travelling from that due to their mass, but by studying the bend which occurred when electrical as well as magnetic forces were brought to bear upon the rays, he was able to obtain a measure which depends upon the mass and not upon the velocity of the particles.

However, it unfortunately happened that these measures were not independent of the electrical charge borne by the single particles, and consequently he was obliged to devise a method for the determination of this charge. The method which he actually used consisted in a simple measurement of the total amount of electricity carried by a large number of the particles, followed by a determination of the number itself. From these two measurements the quantity of electricity carried by one particle could obviously be calculated.

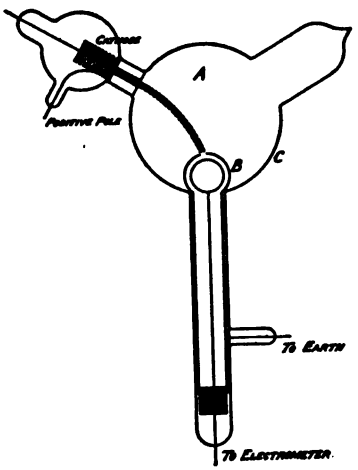


Fig. 19

HOW THE CATHODE RAYS MAY BE BENT BY A MAGNET

This drawing represents a cross-section of a tube which was employed by J. J. Thomson in the study of the cathode rays. It is seen that after the rays enter the large bulb *A* they move along a circular path. This is due to the presence of a magnet which is placed outside of the bulb in such a way that the lines of magnetic force between the opposite poles of the magnet are perpendicular to the path of the rays. The magnet is omitted from the drawing so that the path of the rays can be clearly shown. However, if it were supposed to be really absent it would be necessary to represent the rays as impinging on the bulb at *C* instead of at *B*, which is an electrical condenser for collecting the charge carried by the rays.

Thomson's procedure for finding the *number* of particles corresponding to a known charge was exceedingly clever. On account of its charge each of the particles is a center of forces of attraction, so that if they exist in an atmosphere over-saturated with moisture, this moisture tends to condense about the individual particles, each of the latter thus becoming the nucleus

Plate III

THOMSON CATHODE RAY TUBE

This is a photograph of a tube of the type represented diagrammatically in Fig. 19, and employed by J. J. Thomson to prove that the cathode rays carry an electric charge. The cathode is on the extreme right, the anode being placed in the middle of the same arm of the tube. The rays originate at the cathode, pass through the hole in the anode, and are deflected by a magnet, placed near the bulb, so that they strike a small insulated cylinder in the arm at the left. This cylinder is connected with an electrometer, which registers the presence of the charge. The lower arm contains materials for controlling the vacuum.

Plate III

THOMSON CATHODE RAY TUBE

This is a photograph of a tube of the type represented diagrammatically in Fig. 19, and employed by J. J. Thomson to prove that the cathode rays carry an electric charge. The cathode is on the extreme right, the anode being placed in the middle of the same arm of the tube. The rays originating at the cathode, pass through the hole in the anode, and are deflected by a magnet, placed near the bulb, so that they strike a small insulated cylinder in the arm at the left. This cylinder is connected with an electrometer, which registers the presence of the charge. The lower arm contains materials for controlling the vacuum.

of a small drop of water. The size of the drops of water thus formed can be determined by the rate at which the fog which they compose settles under the pull of gravity. Since it is easy to measure the total amount of water which condenses, the number of droplets in the fog can be calculated from a knowledge of their individual size. Since each droplet corresponds to a single electrical particle the number of droplets gives a measure of the number of such particles which are present, and hence permits the calculation of the charge which they individually bear.

Knowing the amount of electricity carried by each particle in the cathode rays, it is possible to separate the effect of the charge from that of the mass, and hence to ascertain the magnitude of the latter. The most refined measurements of this sort show that the cathode ray particles, which are now called *electrons*, have a mass which is about one eighteen-hundredth that of the lightest known atom, that of hydrogen.

Sources of electrons other than the cathode rays are now available, and the nature of electrons has been satisfactorily proved to be independent of their source.

The Size and Shape of the Electron. — The *size* of the electrons is calculated by use of the fundamental laws of electrical action. These laws imply that electrical charges, even when free from all matter in the ordinary sense of the word, possess one of the most characteristic properties of matter, viz., mass or inertia. The laws state, furthermore, a definite relationship between the charge of an electrical particle, its volume, and its mass, such that for a given charge the mass increases as the volume decreases. Since we know the mass and the charge of the electron from the measurements described above, it is possible to calculate the volume. This calculation is

based upon the assumption that the electron is made up of pure negative electricity and of nothing else, *i.e.*, that it contains no "matter," as distinguished from electricity. Although it is difficult to give a direct justification of this assumption it is nevertheless in harmony with all of the analogies of the situation, and is contradicted by none of the facts. Studies in radio-activity have shown that electrons can pass straight through considerable thicknesses of solid substances and, indeed, through the atoms themselves. This clearly suggests that the electrons are very minute, as is indicated, also, by the calculations.

The symmetry of structure of the electron seems to be borne witness to by certain measurements regarding the manner in which its mass changes with its velocity. It follows from the fundamental electrical laws mentioned above that the electronic mass will increase at high speeds in a way which depends in its details upon the shape and also upon the internal structure of the electron. By calculating the masses which should be effective at different speeds for various probable types of electronic constitution, and then comparing these results with actual measurements we can obtain some idea as to the real shape and structure of the electron. At present the electron is believed to be spherical at low speeds, but it is thought that it becomes more or less flattened in the direction of motion when it moves at speeds approaching that of light.

REFERENCES

A considerable number of popular discussions of the electron and its measurement are obtainable. Among these may be mentioned the following:

R. K. Duncan's "The New Knowledge" (1908), Part 3, Chapters III to X, inclusive.

Sir Oliver Lodge's "Electrons" (1907), Chapters III–XIV inclusive.

Harry C. Jones' "The Electrical Nature of Matter and Radio-Activity" (1906), Chapters I–III inclusive.

E. E. Fournier D'Albe's "The Electron Theory" (1906), Chapter XI.

Section 26

THE IMPORTANCE OF ELECTRICAL FORCES IN NATURE

The meaning of the statement that "most of the phenomena in nature are due, in the last analysis, to electrical attractions and repulsions," will become clear to the reader as he proceeds. Part of its significance can be grasped at the present stage of the discussion if one remembers what has been said in Section 8 about the dependence of the properties of substances upon the nature of their internal forces. There is now little doubt that these forces are electrical. Also, chemical action and all electrical phenomena clearly involve the agency of electrical forces. When we come to study the question of the constitution of the atom we shall see that the phenomena of radio-activity, and the emission and absorption of light, have an electrical origin.

REFERENCES

See Sir Oliver Lodge's "Electrons" (1907), Chapter XVI.

Section 27

THE REACTIONS OF ELECTRONS AND CHARGED ATOMS

How Ions are Produced. — When an electron is taken from or added to a previously neutral atom or molecule the charged particle which is thus formed is called an "ion" and the process is that of "ionization." Various means of ionization are known. The collision of molecules

in the course of their heat vibration may sometimes be sufficiently violent to knock electrons out of the molecules. A more effective process of a similar nature, however, lies in the bombardment of a gas with flying electrons or ions, which on account of their speed and the electrical forces which they exert upon the electrons within the gas molecules are able in many cases to bring about a separation of the two. C. T. R. Wilson, by bringing about the condensation of moisture on the ions which are formed, has been able to obtain accurate photographs of the path of the flying *a* particles from radium through a gas. A powerful electrical field — such as that which exists between the terminals of a sparking induction coil — will cause ionization. Light (including X rays), being a form of electrical energy, can also separate electrons from the atoms with which they are combined. Ionization is likewise a common accompaniment of chemical action, and occurs in many chemical solutions, a fact later to be considered in greater detail (see Section 29).

A definite amount of energy is required to force an electron out of any atom, an amount which varies only slightly with the nature of the atom. The differences which exist, however, are sufficiently constant to constitute characteristic properties of the elements. The energy of ionization of a substance can be estimated from the intensity of the electrical field needed to just produce ionization.

The Interactions of Ions and Electrons. — As explained in Part I an "uncharged" atom contains a certain number of electrons and also positive electricity, enough to neutralize exactly their negative charges. If an electron is added to the atom from the outside there will be more negative electricity than positive and the atom will have a "negative charge"; whereas if an electron is taken away from it there will be more positive than negative elec-

tricity and the atom will have a "positive charge." (7) in Figure 20 shows two uncharged atoms, (4) two negatively charged ones, and (5) two positively charged

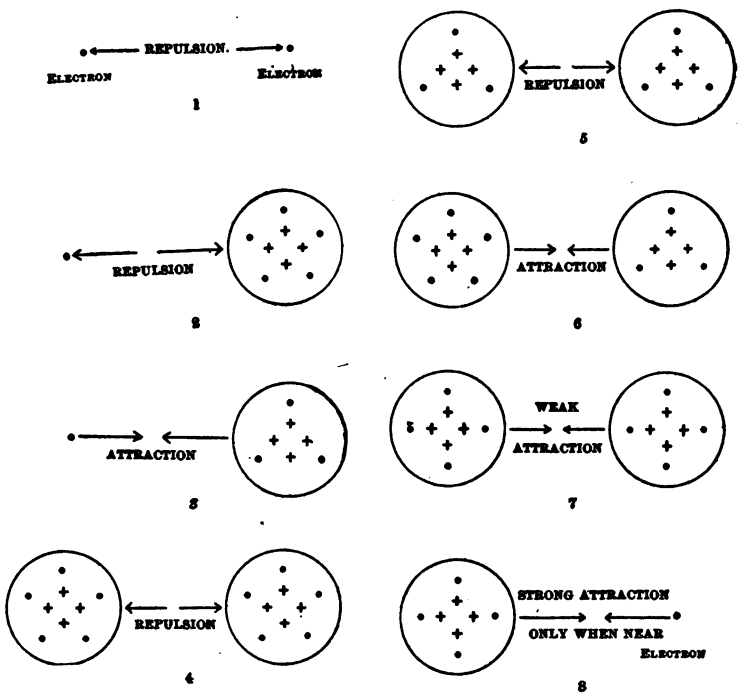


Fig. 20

THE FORCES ACTING BETWEEN IONS, ATOMS AND ELECTRONS

These diagrams represent in a symbolic way the forces which operate between aggregates of electrical charges, of various degrees of complication. The diagrams are explained in the text.

ones. It must be borne carefully in mind that these *are not pictures of atoms.* They are merely symbolic drawings, the black dots representing electrons, and the

"plus sign" representing the positive charge which is inseparable from the atom.

It follows of course from the laws of electricity, as recalled to the reader in Chapter V under the heading, "The Two Electricities," that the following statements are true:

(*a*) Two electrons *repel* each other [see (1), Figure 20].

(*b*) An electron is *repelled* by a negatively charged atom (*i.e.*, one which has one electron too many for neutrality (2).

(*c*) An electron is *attracted* toward a positively charged atom (*i.e.*, one which has one electron too few for neutrality) (3).

(*d*) Two negatively charged atoms *repel* each other (4).

(*e*) Two positively charged atoms *repel* each other (5).

(*f*) A positively charged atom and a negatively charged atom *attract* each other (6).

There are also two attractions of a different kind, one of which is already familiar to the reader, which do not follow obviously from the fundamental electrical laws. These are:

(*g*) All atoms *attract* each other, even when they are neutral (7). This is the familiar attraction considered in Section 10. It explains the cohesion of solids and liquids in spite of the violent heat vibration to which their atoms and molecules are subject. This attraction, unlike the common "electrical" attraction (*f*), is effective only when the two atoms are very near each other.

(*h*) All uncharged atoms *attract* electrons (8). This force, like (*g*), is only effective when the electron is very near the atom. When it is near, however, the force becomes very great. At greater distances it is very much weaker than the familiar "electrical" forces before mentioned.

REFERENCES

Concerning ionization, consult "The Electron Theory" by E. E. Fournier d'Albe, Chapter IV; "Electrons," by Sir Oliver Lodge, Chapter VII; "Modern Theory of Physical Phenomena" by Augusto Righi (1904), Chapter IV.

Section 28

SOME EFFECTS CONNECTED WITH THE ELECTRICAL CURRENT

The "Hall Effect." — It follows from a fundamental law of electrical science that when a moving electron comes under the influence of a magnet its normally straight-line path will be changed to a curve. Hence if the conduction of electricity through solids actually consists in the bodily motion of electrons it should be possible to alter the direction of an electric current in a wire by bringing a sufficiently powerful magnet near it. Experiment shows that this can be done, the phenomenon being commonly known as the "*Hall effect.*" There are certain stubborn difficulties in connection with the explanation of the Hall effect, because the changes are sometimes in one direction and sometimes in the other, but it seems highly probable that the phenomenon is due to electron deflection.

The Nature of Electrical Resistance. — Different metals — and substances in general — vary widely in their so-called electrical conductivity, or to put it the other way round, they offer varying degrees of "resistance" to the passage of the electrical current. There are various factors which determine the electrical conductivity or resistance of substances. In the first place, it should be clear that the more electrons a substance contains in a given volume the more electrons will move forward when

an electrical force is applied to it. The "current" or "amperage" is merely the amount of electricity which flows through a certain portion of the wire in a given time, or, in other words, the number of electrons which pass any fixed boundary. So it is obvious that the more electrons there are free to move the greater will be the current under a given electromotive force or "voltage," and therefore the higher the conductivity of the substance or the lower its resistance. Substances such as hard rubber and porcelain contain almost no free electrons and hence are what we call "non-conductors" or "insulators." Metals like copper and silver contain a large number of free electrons and accordingly are "good conductors."

Electrical and Thermal Conductivity. — In Section 20 the fact is mentioned that the extraordinarily good heat conductivity of metals is accounted for in terms of the free electrons which they contain. If this is the true explanation it can be shown to follow that, other things equal, those metals which contain the largest number of free electrons will be the best heat conductors. But such metals will also be the best conductors of electricity, and hence it would appear that some sort of proportionality should exist between the power of a substance to conduct heat and its power to conduct electricity. Accurate measurements and calculations show that a relationship of this kind holds in nature, and that its quantitative character is in remarkable accord with the assumptions of the electronic and molecular theories.

Besides the number of free electrons in a unit volume of a substance there are other factors which must influence its conductivity. One of these is the "mean free path" of the electrons among the molecules of the substance (see Section 13). Other things being equal, the

farther an electron can move without striking an atom or another electron the better the substance will conduct both electricity and heat.

It is interesting to note the fact that the direction of movement of the electrons in a wire is opposite to the so-called direction of the current, for the reason that the latter is what would be the line of motion of *positive* electricity if any were moving. The electrons, it will be remembered, are negative. When they move oppositely to positive particles the two produce identical magnetic effects. If electrons had been known when the terminology was developed, the conventional direction of the current would probably be the reverse of that now in use.

REFERENCES

The following references are to simple discussions of the theory of electrical conduction in solids:

E. E. Fournier d'Albe's "The Electron Theory," Chapter IV, Section 4.

Sir Oliver Lodge's "Electrons," Chapter X.

D. F. Comstock: "The Modern Theory of Electric Conduction," in the "Transactions of the American Electro-Chemical Society" (1912), Volume XXI, pp. 41–48.

A somewhat mathematical and more detailed account is given by Sir J. J. Thomson in his "Corpuscular Theory of Matter" (1907), Chapters IV and V.

Section 29

ELECTRICAL CONDUCTION IN GASES AND LIQUIDS

Conduction by Ions; Electrolysis. — Metals are not the only substances which are good conductors of electricity. It is a well-known fact that many solutions are excellent conductors, and in this case the conduction involves the motion not of free electrons but of charged atoms or "ions." Some of these moving atoms are negatively

charged, that is, bear electrons in excess of their normal number, while others are positive and have lost part of their regular complement of electrons. The current through the liquid consists of negative atoms or ions moving in one direction and of positive atoms or ions moving in the opposite direction. Both of these lose their charges when they come into contact with the "electrodes" by which the current enters and leaves the solution, the former at the positive pole and the latter at the negative pole. This means that atoms of the positively charged substances will collect about the negative pole while those of the negatively charged kind will segregate about the positive electrode. This process is commonly called *electrolysis*, and will be further discussed at another point. For this type of conduction it is necessary for the liquid to contain ions. (See Section 27.)

The conduction of electricity through gases also depends upon the presence of ions. Free electrons, however, are often present and active. To the study of phenomena connected with the passage of electricity through gases we owe a great deal of our knowledge of the nature of electrical processes in general, since the conditions here are particularly favorable for observation.

REFERENCES

On the conduction of electricity through gases see W. C. D. Whetham's "The Recent Development of Physical Science" (1904), Chapter V.

Sir J. J. Thomson's great work "The Conduction of Electricity Through Gases" should also be mentioned.

On conduction in solutions, see Augusto Righi's "Modern Theory of Physical Phenomena (1904), Chapter I, and "The Theory of Electrolytic Dissociation," by Harry C. Jones (1900).

Section 30

THE ELECTRICAL TRANSMISSION OF POWER

The analogy between the transmission of power by electricity and by compressed air really amounts to something very close to identity, if the modern view is correct. When air is pumped in at one end of a pipe the air molecules at that end exert an increased force upon the others further along and thus increase the pressure throughout the system. Similarly, in an electrical circuit an increase in voltage may be thought of as corresponding to the introduction of further electrons into that part of the circuit which lies just beyond the dynamo or battery. These repel neighboring electrons and thus the electrical pressure increases all along the circuit.

Ordinarily the electrons are confined within the body of the wire just as the air molecules are held within the pipe. Leaks, however, may occur — as in the case of compressed air systems — as shown by the glow which sometimes surrounds high tension lines at night.

The influence of electrons upon each other's motions of course depends in large part upon the enormous electrical repulsions which exist between them. This is not so clearly the case with molecules.

REFERENCES

See E. E. Fournier d'Albe, "The Electron Theory" (1906), Chapter VII.

Section 31

THERMO-ELECTRICITY

The Principle of the Thermopile. — Roughly speaking, the number of free electrons in a substance is a measure of the lack of affinity of its atoms or molecules for electrons. The fact that this affinity varies for different sub-

stances has some interesting consequences quite apart from the production of various degrees of electrical conductivity. For example, if two metals the atoms of one of which have a greater affinity for electrons than have those of the other, are placed in contact the former will appropriate electrons from the latter. This is due to the fact that the "evaporation of electrons" from the surface of one of the metals is more rapid than that from the surface of the other metal, so that the first gives out to the second more electrons than it receives. Hence the second metal becomes negatively charged, while the first acquires a positive charge.

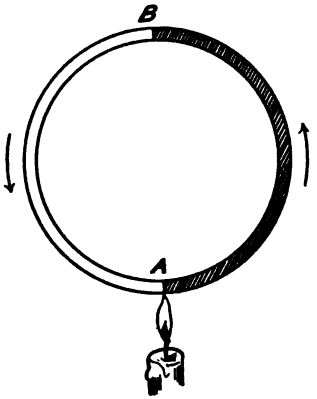


Fig. 21

A THERMO-ELECTRIC CIRCUIT

This is a symbolic drawing. The circle as a whole represents the complete electrical circuit, the left half being composed of a metal which emits electrons freely and the right half of one which parts with its electrons less easily. If the junctions *A* and *B* are both at the same temperature no current will flow, since the tendency towards a clockwise current which exists at *B* is exactly balanced by the opposite tendency existing at *A*. However, when the junction *A* is heated these tendencies are no longer exactly in equilibrium and electrons move around the circuit in the direction of the arrows. It is not necessary that the circuit should be made up of equal masses of only two different metals. It may be broken at any point and long wires of any sort of conducting substance introduced without altering its general principle.

If we suppose the two metals in question to be in the form of horse-shoe shaped wires touching each other at their extremities it can easily be seen that no current of electricity will flow through the circuit which is thus formed, for the reason that the electrical forces which exist at one junction are exactly balanced by those existing at the other junction. Suppose, however, that the latter is heated to a temperature higher

than that of the former. (See Figure 21.) This will bring about a change in the electrical forces at the point which is being heated, due in part to the fact that the number of electrons thrown off by one metal increases with the temperature faster than the number emitted by the other metal. The electrical equilibrium of the circuit is thus disturbed, and a current will flow, that is, electrons will move from one junction towards the other. This motion of the electrons carries heat energy from the hot to the cold junction so that continued heating and cooling is necessary in order that it should persist. This is the principle of the so-called thermopile.

The Thermo-Electric Series of the Metals. — By studying different thermo-electric circuits of the sort described above we can arrange a series of metals in which by contact with a standard metal, each member of the series gives a higher voltage than the member preceding it. It is found that this series has close affinities with another series which is determined by studying the voltages generated by the same metals in the form of an ordinary electrical battery. The exact nature of the electro-motive series varies with the temperature, on account of the fact that as different metals are heated the number of free electrons which they contain in a given volume does not necessarily alter in the same way. A sample sequence is represented below:

THERMO-ELECTRIC SERIES OF METALS

Metal	Relative Potential Difference
Bismuth	89 to 97
Nickel	22
German-silver	11.75
Lead	0
Platinum	− 0.9
Copper	− 1.36
Zinc	− 2.2
Iron	− 17.5
Antimony	− 22.6 to − 26.4
Tellurium	502.
Selenium	800.

Lead is taken as the standard metal.

REFERENCES

On thermo-electricity, consult: E. E. Fournier d'Albe's "The Electron Theory" (1906), Chapter V.

See also: O. W. Richardson's "Aggregates of Electrons," in the "Proceedings of the American Philosophical Society" (1911), volume 50, pp. 347–365, and

W. C. D. Whetham's "The Theory of Experimental Electricity" (1912), Chapter VI.

On the evaporation of electrons see N. Campbell's "Modern Electrical Theory," second edition (1913), pp. 81–84.

Section 32

CHEMICAL AFFINITY

Electro-positive and Electro-negative Elements.— Chemical affinity may perhaps be regarded as another expression of the fact that different kinds of atoms have varying degrees of attraction for electrons. It has been known for a long time that the chemical elements could be grouped into three not very sharply defined classes, those which were characteristically electro-positive, those characteristically electro-negative, and those which might be either electro-positive or electro-negative, according to the circumstances. Hydrogen and the metals are the most powerfully electro-positive of the elements, while such substances as oxygen, chlorine, fluorine, etc., are strongly electro-negative. As we have seen, the former lose electrons easily; the latter, on the other hand, appropriate with great avidity electrons not their own.

It is clear that when a neutral atom of hydrogen, for example, parts with an electron it must become positively charged, and if this electron or another is appropriated by an atom of chlorine, for instance, the latter becomes negatively charged. Positively and negatively charged atoms of this sort will obviously tend to combine, owing

to the electrical attractions existing between them, and these attractions, it seems probable, constitute chemical affinity.

When we study the actual constitution of chemical compounds we find that the most common compounds are made up of just such electro-positive and electro-negative components. Common salt, for example, is composed of the strongly positive element sodium, combined with the strongly negative element chlorine.

Any Element may be Positive or Negative. — However, if we make a table of elements which we suppose to be electro-positive and another of those which we suppose to be electro-negative, we soon discover that, however we may construct the table, exceptions always occur to a rule which states that only atoms of opposite sign combine with each other. For a long time it was thought that the fact that two negative or two positive atoms could combine chemically was a refutation of the electrical theory of chemical affinity, since atoms bearing charges of like sign could only repel each other. The electron theory removes this difficulty, along with others, for any atom can become negatively charged if it can gain an electron, or positively charged if it can lose one, and the same atom may conceivably suffer either of these changes according to the conditions under which it is placed. No two of the elements have the same affinity for negative electricity, and if any two of them are mixed under proper conditions the atoms of the one having the lesser affinity will lose electrons while the atoms of the other will gain them. Mixed with a different element, the same atoms which here gain electrons might lose them, if the element in question were the more strongly electro-negative. In other words, we can speak of the electro-negativity or positivity of the elements in a relative sense only.

There is one difficulty which remains outstanding, however, and that is the explanation of the chemical affinity which apparently exists between atoms of the same species. We have already mentioned the fact in Section 7 that almost all of the elements form complex molecules even in the pure state. This implies the existence of chemical affinity between atoms of the same kind. Such affinity is probably to be explained by the idea that the positive and negative charges within any atom are not uniformly distributed throughout it, and hence that the surface of an atom is, so to speak, *mottled*. Two atoms of the same kind may thus stick together by electrical attraction if, as diagrammatically represented in Figure 22, they are so oriented with respect to each other that the negative mottlings of one coincide with the positive mottlings of the other, and *vice versa*.

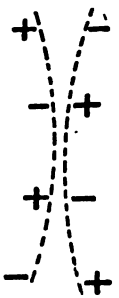


Fig. 22

SHOWING THE MANNER IN WHICH TWO NEUTRAL AGGREGATES OF ELECTRICAL PARTICLES MAY ATTRACT EACH OTHER

The two arcs represented in the figure may be thought of as cross-sections through the surfaces of two adjacent atoms which are in chemical union. The surfaces are so disposed with respect to each other that the negative components of the one attract the positive components of the other. Taken as wholes both atoms are electrically neutral, but at close range powerful mutual attractions may still exist between their parts. This diagram must not be regarded as an accurate picture of the surface of an atom.

The "Inert" Elements. — Some of the elements, such as argon, helium, and the like, are chemically inert, that is, they refuse to combine with any other elements. The reason for this probably lies in the fact that they are incapable of becoming permanently ionized, that is, they

have neither a very strong tendency to gain additional electrons or to part with those which they naturally possess, but rather tend to be stable in this respect. We have mentioned the fact in Section 6 that the electrical character of the elements varies with other of their properties according to the law of the periodic table. The inert elements all fall into the same family, and each of them lies between a strongly electro-negative element on one side and a strongly electro-positive element on the other, so that it is perhaps not surprising that they should be neutral.

REFERENCES

See the reference, already given, to Sir Oliver Lodge's "Electrons," Chapter XVI, and Norman Campbell's "Modern Electrical Theory," second edition (1913), Chapter XIII, esp. pp. 340 *ff.*

Section 33

SOLUTION AND ELECTRICAL DECOMPOSITION

How Water "Ionizes" Dissolved Substances. — It has been asserted in the course of our discussion that the forces of chemical affinity are probably electrical. If this is true, any influence which tends to weaken these forces should cause the molecules to fall apart under the influence of their heat vibrations.

Now all substances possess a property called dielectric capacity, which can easily be measured, but concerning the exact nature of which we need not here trouble ourselves. Suffice it to say that the electrical forces between any given set of charged particles become less as the dielectric capacity of the medium in which they are placed becomes greater. All material bodies have a higher dielectric capacity than has empty space and it would seem that if two bodies rightly selected could come

into sufficiently intimate contact with each other the large dielectric capacity of the one might bring about a separation of the electrical particles making up the other. Just this intimacy of contact is assured when one of the substances is a liquid and the other is in solution within it. Suppose, for example, that a solid like common salt, the molecules of which are made up of one atom of chlorine and one atom of sodium, is dissolved in water. According to our view of chemical affinity, these molecules are held together by the attraction which exists between the positively charged sodium atom, Na^+ and the negatively charged chlorine atom, Cl^-. If the properties of the water cause it to weaken this attraction so that the oppositely charged parts of the salt molecules can be knocked apart, the solution will contain free charged atoms, or ions. This process actually occurs with a great many substances which can be dissolved in water. It is called technically "electrolytic dissociation."

The Motion of Ions Through a Solution. — When solutions conduct electricity the current is due to the bodily motion of the ions which have been produced by the splitting up of the molecules of the dissolved substance. We have discussed this matter in Section 29, and have also referred to some of the related phenomena in Section 2.

The electrical dissociation of the molecules of dissolved substances, which can easily be proven by experiment to exist, furnishes us with another striking verification of the idea that chemical affinity depends upon electrical forces.

The Effect of Ionization on Boiling and Freezing Points. — When any substance is dissolved in a liquid, the boiling point of the liquid is raised and its freezing point is lowered to an extent which is approximately proportional

to the number of molecules which have entered into solution. The cause of these changes can be stated in terms of the kinetic molecular theory. The important fact for us to notice here, however, is that when the molecules of the dissolved substance are split up into ions the number of effective molecules is thereby greatly increased, and that if this is the case the effect upon the boiling and freezing points should be greater than would be expected upon the assumption that no such splitting of the molecules occurred. Empirical measurements appear to verify this conclusion, and also show the presence of an abnormally high osmotic pressure (see Section 19) in solutions of electrically dissociated substances.

REFERENCES

Refer to Nernst's "Theoretical Chemistry" (1911), Book II, Chapter VII, or Talbot and Blanchard's "The Electrolytic Dissociation Theory, etc." (1907).

W. C. D. Whetham's "The Recent Development of Physical Science" (1904), Chapter IV.

A complete book on this subject is Whetham's "Treatise on the Theory of Solutions" (1902).

Section 34

CHEMICAL VALENCY

It is a well-known fact that the chemical elements combine with each other in proportions which vary with the element which is considered. For example, one atom of chlorine normally combines with only one atom of hydrogen, while an atom of oxygen usually combines with two of hydrogen. A single carbon atom, on the other hand, will as a rule unite with four hydrogen atoms. The number of hydrogen atoms with which an atom of a given element will combine is called the "valency" of

the element. Some active elements do not combine readily with hydrogen, but these unite with oxygen, the valency or combining power of which is known to be two.

The valency of an element is not perfectly constant, but it is nevertheless fairly characteristic. Its magnitude probably depends upon the affinity of the atoms of the element for electrons. The valency of an element in any specified compound represents the number of electrons which one of its atoms has either gained or lost.

REFERENCES

See R. K. Duncan's "The New Knowledge" (1908), 166–167, and N. Campbell's "Modern Electrical Theory," second edition (1913), pp. 340–350.

Section 35

CHEMICAL ACTION

Chemical action is not as straightforward a process as would at first appear, since it must depend upon the random collision of the reacting molecules or atoms.

Let us consider carefully a case of chemical combination or "synthesis" and see if we can visualize for it a reasonable mechanism.

The Basis of the Law of "Chemical Mass Action." — We start with a certain number of atoms of the species A and an equal number of the species B, which are capable of combining with each other in the proportion of one to one. However, they cannot do this unless all of the individual A atoms come into intimate contact with as many different B atoms. All of the atoms are bounding about at random and colliding with each other like the members of a panic-stricken crowd, and not every collision that occurs is between an A and a B atom. This will

be especially true after a sufficient number of favorable collisions have occurred, so that the reaction has progressed some distance, for at this time the mixture will contain not only separate A and B atoms but also the AB molecules which have been formed. When these collide with each other and with the atom, no union occurs, so that as the reaction proceeds the number of collisions favorable to chemical combination constantly decreases.

It will be observed that this decrease in the number of favorable collisions is caused by a diminution in the number of reactable atoms which are present. Now the *rate* or "velocity" of any chemical reaction consists in the number of molecules which are formed or decomposed in a given time, and this, in turn, must depend upon the number of collisions occurring in that time. From this it becomes clear that as a reaction proceeds, its velocity should constantly diminish, and it can be shown in fact that at any time this velocity is proportional to the number of active atoms or molecules of each kind which remain. This is the *law of chemical mass action*, which is of the utmost importance in the study of chemical change.

Chemical "Equilibrium." — The reaction which we have considered above would be complete when each of the A atoms had combined with a separate B atom. It would take a long time for such a reaction to reach completion, for the reason that when nearly all of the atoms had combined, the remaining ones would be separated by a multitude of inert molecules and so would have small chance of encountering each other. However, in reality most chemical changes are *reversible*, that is, the molecules which are formed by the reaction tend to break up again and reproduce the original substances. Thus, most reactions will consist in two types of change, a forward and a reverse. When the reaction commences, the for-

ward change is the most rapid because there are more molecules to enter into it, but as the reaction progresses the products of this change pile up, and consequently necessitate a constant increase in the reverse reaction. There finally comes a time, of course, when the rates of the two opposite changes are equal so that they balance each other. At this time the "equilibrium point" of the reaction is said to have been reached, and apparently all chemical change has ceased. This appearance is deceiving, however, for beneath the seeming quiet there goes on a ceaseless balanced activity. It is characteristic of the modern view of things to suppose that nearly all cases of seeming rest are in reality cases of balanced motions.

REFERENCES

On the law of chemical mass action, see W. Nernst's "Theoretical Chemistry" (1911), Book II, Chapter I.

Also: G. Senter's "Outline of Physical Chemistry" (1908), Chapter VII.

Harry C. Jones' "The Elements of Physical Chemistry" (1902), Chapter IX.

Section 36

EFFECTS AND CONDITIONS OF CHEMICAL CHANGE

The Heat Produced by Chemical Change. — It is a well-known fact that when chemical changes occur, energy is usually liberated in one form or another, most commonly as heat. If atoms are to combine, under the influence of chemical attraction they must first move towards each other in response to this attraction, and in so doing they must acquire energy of motion. Hence, in general, the temperature of the reacting substances increases in proportion to the strength of the chemical affinities which are active.

The Generation of Light and Electric Current. — Chemical change may produce electrical effects if the conditions are arranged as in the ordinary "battery," so that charged atoms which are free to move can combine with the atoms of a solid electrical conductor and deposit their charges, so that the conductor as a whole is electrified and tends to become the origin of an electrical current. The production of light by chemical change may be due to the fact that light is caused directly by the vibration of the electrons which are active during the change, or it may be indirectly caused through the rise in temperature brought about by the reaction.

Conditions Favoring Chemical Action. — Almost all chemical changes involve not only the formation of new molecules but also the breaking up of old ones, and since the decomposition of molecules would tend to be favored by the collisions of the molecules in their heat motion, we should expect for this reason alone that the rapidity of a chemical change would increase with the temperature. As mentioned in Part I, the transfer of electrons from one atom to another must also take place more readily at high than at low temperatures, and this, too, aids the reaction.

In the case of reaction between gases, *high pressures* are favorable to chemical reaction, since the more molecules there are in a given volume the more frequently they must collide and hence the greater their chances of decomposition and recombination. Another important condition favoring chemical change is the presence of a *catalyzer*, which is merely some foreign substance capable of accelerating a reaction without being changed itself. The exact general mechanism by which *catalysis* is produced is not clearly understood, but it is probable that the catalyzer is an ionizing agent of some sort.

"Chemical energy," which is utilized when coal, for example, is burned under the boiler of a steam engine, is really the energy of attraction of charged atoms or groups of atoms. Human life and industry, to-day, depend absolutely upon the presence and application of this energy.

REFERENCES

On the energy relationship of chemical change, consult W. Nernst's "Theoretical Chemistry" (1911), Books III and IV.

Section 37

LIGHT WAVES AND LINES OF ELECTRICAL FORCE

The Present Status of the "Æther."—Experiment shows that light has many of the properties of some sort of wave motion. Since it is difficult to imagine a wave without thinking of some substance in which it is a wave, physicists have been accustomed up to recent years to assume the existence of an all-pervading æther, the undulations of which constitute light and other similar disturbances. Of late, however, certain very important experimental and theoretical results — clustering around what is called the "principle of relativity"—have thrown a great deal of doubt upon the existence of the æther, so that it is now advisable to conceive of a light wave in a somewhat different way.

The Nature of Electrical Force Lines. — Nearly everyone is familiar with the fact that the state of affairs in the space around a body which is charged with electricity can be represented by what are called "lines of electrical force." These lines show in a symbolic fashion how another charged body placed in the space in question would tend to move, or, in other words, what forces would act upon it. It is probable that these lines of force have

some counterpart in reality, and recent developments make it not improbable that electrons and other charged particles of atomic or sub-atomic size are actually centers of radial "tubes of electrical force."

"Kinks" in Electrical Force Lines. — It can be shown that lines of electrical force, if they exist, must possess "inertia," that is, that they must offer resistance to changes in their state of motion or rest. In other words they act as regards motion very much like a stiff rope or wire attached to the electron or other charged particle. Hence if the electron is suddenly set into motion or if, when in motion, it is suddenly brought to rest, its lines of force will not accommodate themselves to this change in motion immediately, but will tend to remain at rest or to keep on moving as they did before anything had happened to the electron. This means that every time an electron is slowed down or is speeded up, and every time the direction of its motion is altered, *kinks* or curves will be formed in its lines of electrical force. The principle of the formation of these kinks is essentially the same as that of the production of waves in a rope, one end of which is shaken. Just as the waves in the rope move away from their source at a definite speed, so the kinks in the electrical force lines travel away from the electron or other charges, with the speed of light. The formation of such "kinks" is illustrated in Figure 23.

If the charge which is under consideration vibrates continuously back and forth, a series of kinks will obviously be formed in its force-lines, and these will constitute waves. As a matter of fact light and many other forms of radiation are probably made up of a series of just such kinks or curves.

Electrons probably do not vibrate or oscillate as much as we were once inclined to believe. It seems more

likely, in the light of recent developments, that they move in "jerks," dropping suddenly from one position to another without an ensuing reverse motion. If this

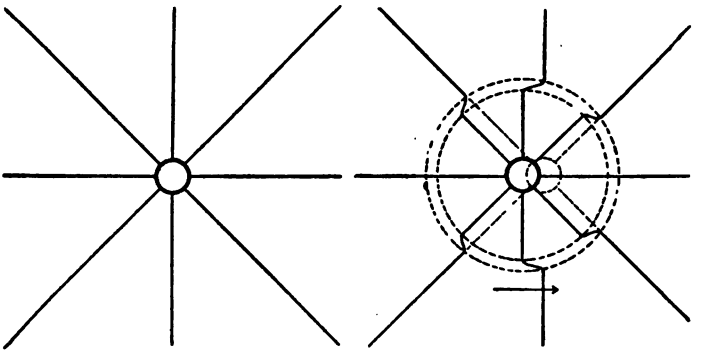


Fig. 23

TO SHOW HOW RADIATION IS PRODUCED BY STOPPING THE MOTION OF AN ELECTRICAL PARTICLE

The diagram at the left represents a charge of electricity with its radiating lines of forces. We will suppose this charge with its lines to be moving uniformly in the direction indicated by the arrow in the diagram at the right. When the charge is suddenly brought to rest the "lines" have a tendency to continue in motion, and do so until, so to speak, the news of the stopping of the charge has reached them. This "news" travels outwards from the charge with the velocity of light, along with the "kinks" in the force-lines which result from the discrepancy between the actual and the "expected" position of the charge. These kinks contain electro-magnetic energy and constitute light and other forms of electro-magnetic radiation. Such radiation is produced whenever any change whatsoever occurs in the state of uniform motion of an electrical charge.

is true it means that the ordinary laws of motion do not apply without modification to the motion of electrons. This question is further discussed in Section 54.

REFERENCES

On the electrical theory of light, consult Righi's "Modern Theory of Physical Phenomena" (1904), Chapter II.

The theory of "kinked" force-lines above discussed was first

developed by J. J. Thomson and one of his simplest accounts of it will be found in his "Electricity and Matter" (1904), Chapters I–III inclusive.

See also W. C. D. Whetham's "The Theory of Experimental Electricity" (1912), Chapter IX.

Section 38

THE ZEEMAN EFFECT

The rapidity with which any vibrating body moves back and forth in its path depends upon the magnitude of the forces which are acting upon it. Magnetic forces are known to act upon moving electrically charged bodies and hence we should expect that if there are electrons vibrating or moving in any way within sources of light, the application of a magnet to such a light source would alter the rate of vibration of these electrons. If this occurs, the vibration time, and hence the "wave-length" of the light, must also be changed. From the mathematical theory of electricity it is possible to calculate the exact change which should occur, assuming a vibrating particle of known charge and mass. Conversely, if we know the change in the character of the light we can estimate the charge and mass of the electrical particle which is emitting the light.

A very large number of observations have been made on the effect produced by magnetic forces upon the light given off by many different substances in the glowing state. All of these observations show that, certainly in the majority of cases, the vibrating, or otherwise moving, particle is an electron.

The alteration of wave-length of the light emitted by a glowing body under the influence of magnetic forces is known to physicists as the "Zeeman effect," after its discoverer Paul Zeeman. (See Figure 24.)

It has been shown by J. Stark that the mode of vibration of the electrons within an atom can also be modified by the application of a strong *electrical* field.

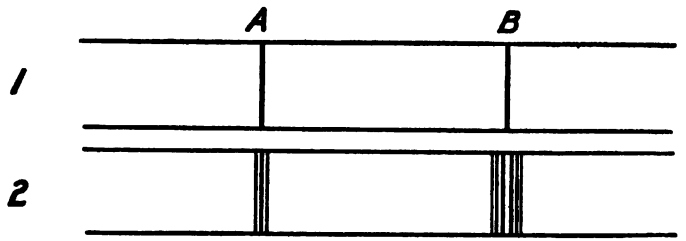


Fig. 24

THE ZEEMAN EFFECT

The two lines *A* and *B* in 1 are supposed to be two lines in the spectrum of a luminous element, such as hydrogen or mercury vapor. When a powerful magnet is applied to the glowing element these spectral lines break up into "triplets" or complex groups of triplets, as shown in 2. This is called the Zeeman effect, and in its simplest form is readily explained by the electron theory.

REFERENCES

See Sir Oliver Lodge's "Electrons" (1907), Chapter XI; E. C. C. Baly's "Spectroscopy" (1905), Chapter XIV, and Norman Campbell's "Modern Electrical Theory," second edition (1913), pp. 146–152.

Zeeman's own account will be found in his "Researches in Magneto-optics" (1913).

Section 39

THE CONDITIONS UNDER WHICH LIGHT IS PRODUCED

Temperature Radiation; The Spectral "Distribution Curve." — There are various special conditions under which material bodies emit light. The one which is most familiar is that of high temperature.

We have already stated that the electrons in bodies take part in the heat vibrations along with the atoms and

molecules, and if this is true they must constantly give off electrical waves. The length of these waves must obviously depend upon the rapidity of the vibrations, and this, in turn, increases with the temperature. Hence, as the temperature of a body containing electrons is raised, the preponderating length of the waves which it gives out should become less. This is exactly what occurs in nature.

When a body is being heated the first perceptible radiations which it emits are "heat waves." When the body becomes "red hot" it is giving off the longest of the light waves, and "white heat," which every one recognizes to be hotter than "red heat," is only possible when green and blue light have been added to the red. The wave-lengths of the blue and green are much shorter than that of red light. With still further increases in temperature, the radiation begins to include still shorter waves which make up the so-called "ultra-violet" light.

On account of the relationship which holds between the temperature of a hot substance and the color of the light which it emits it is possible to get an idea of this temperature by means of observations upon the color of the body. The so-called "optical pyrometer" is an instrument based upon this principle, which does for very hot bodies what an ordinary thermometer does for cooler ones.

As we have seen in Section 23, all of the molecules, and hence all of the electrons, in a body are not moving at the same velocity even if the temperature is throughout what we call "uniform." Some are moving faster and others slower, according to the "law of distribution of molecular speeds," as explained in the Section referred to. Owing to this fact we should not expect the light from a body at a given temperature to be all of the same wave-

length. Supposing that the particles whose vibrations are responsible for the light are electrons, it is possible to calculate the wave-length of the light corresponding to the "average molecular energy" which is characteristic of a given temperature. Since there are more electrons moving at a velocity corresponding to approximately this energy than at any other (approximate) velocity, we should expect most of the light to be of (approximately) the calculated wave-length. Measurements verify this expectation and also the idea that the electron is the actual source of the radiation. The form of this "curve of distribution" of energy in the spectrum of a solid at various temperatures is shown in Figure 25.

But there are electrons moving at speeds both higher and lower than this "average speed," and hence there should be light to correspond, although such light should be less intense, the further its wave-length departs from that belonging to the "average speed." Observation validates this conclusion also.

However, the so-called law of the distribution of light intensities along the spectrum for any given temperature is not exactly what should be expected from the molecular theory, in its ordinary form, and the efforts of physicists to explain its deviation from the expected form have finally culminated in the modern "quantum" theory of light which is discussed in another place (see Section 54).

The theory of temperature radiation is based primarily upon the conception of a "*black body*," which is a body absorbing all radiation impinging upon it and showing a minimum of selectivity in its emission of radiation.

The Emission of Light by Gases. — Gases as well as solids give off light under the right conditions. It is only

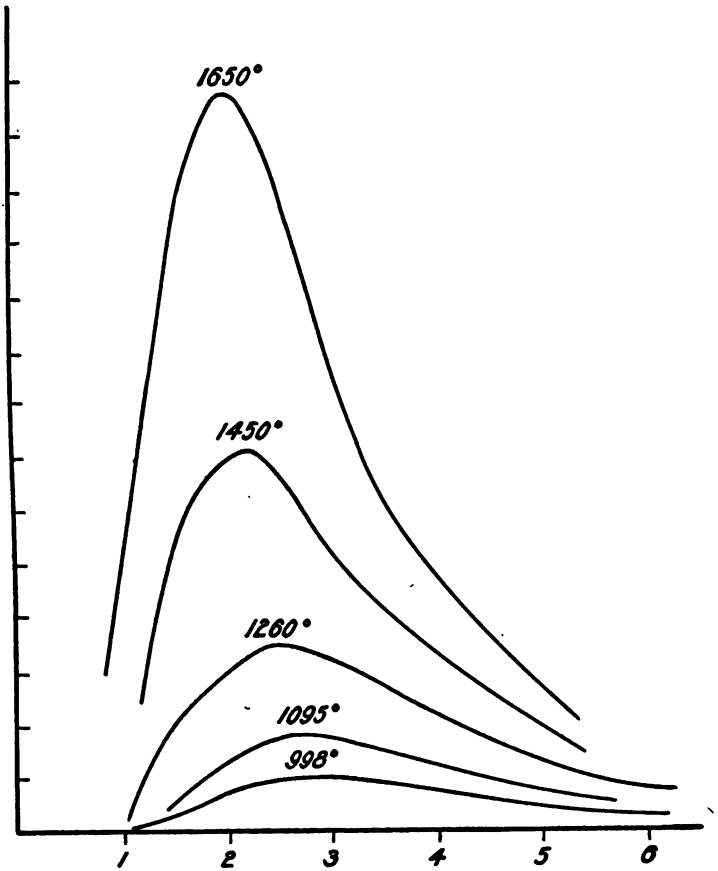


Fig. 25

CURVES SHOWING THE RELATIVE INTENSITIES OF RADIATION OF DIFFERENT WAVE LENGTHS EMITTED BY SOLID BODIES AT VARIOUS TEMPERATURES

The numbers along the horizontal scale represent the wave-length of the radiation (light or heat) in thousandths of a millimeter. The vertical scale represents the relative intensity of the radiation. It will be observed that the curves for the higher temperatures (given in degrees Centigrade) have their maxima at points corresponding with shorter waves than those characteristic of the lower temperatures. The meaning of this fact is explained in the text. These curves are those of the so-called "black body radiation."

when a substance is in the gaseous state that its characteristic "spectrum" can be obtained distinctly.

It has not generally been considered possible to cause a gas to glow simply by heating it. The reason for this is to be found in the fact that under ordinary conditions gases contain very few *free electrons* or ions, and that even high temperatures will not produce a sufficient number of these to make the gas luminescent.

In order to accomplish this end, it is necessary either to send an electrical current through the gas or to permit chemical action to take place within it. We have seen in Section 27 that both of these conditions favor ionization. Ions can be formed in a gas only when electrons are "knocked out" of the atoms which make up the gas, and it is the change in the "mode of motion" of the electrons which occurs either when they are being ejected from or when they return to the atoms which gives rise to the glow that accompanies (say) the electrical discharge through the so-called "vacuum tube." The light of the familiar "mercury vapor arc" depends upon the same principle.

"*Line Spectra.*" — The light which is given off by glowing gases differs from that emitted by solids in respect to its "distribution" along the spectrum. Practically all of the energy in the former case is concentrated about certain definite wave-lengths, the positions of which are not only constant for a given gas, but are different for different gases. The "spectrum" of a glowing gas, then, shows a series of "lines" of colored light in place of the continuous rainbow band which is produced when light from a white hot metal is passed through a prism. This special nature of the spectra of substances in the gaseous condition must be attributed to the fact that the electrons in such substances have much less freedom of movement than have those within a metal, so that they

can only execute vibrations of a few definite frequencies, as determined by the structure of the atoms and molecules of the substance.

The study of the line spectra of the various elements in gaseous form has shown that in any single element the lines can be arranged into "series," such that the positions of the individual lines in these series — that is, the wave-lengths of the lights composing them — can be calculated from relatively simple mathematical formulæ. The exact nature of these formulæ differs from element to element, although it retains important points of identity throughout. It has for some time been recognized, on the basis of the Zeeman effect (which we have discussed in Section 38), that the partial cause of this identity lies in the fact that, in all of the cases considered, the light is emitted by electrons. Only recently, however (see Section 53), have physicists been able to suggest a way in which the relatively simple electronic structure attributed to such atoms as that of hydrogen could be consistent with the very complex nature of their line spectra.

REFERENCES

A complete but elementary discussion of the various forms of electro-magnetic radiation is given in S. P. Thompson's "Radiation" (1898).

A more modern treatment is the excellent one by N. Campbell in his "Modern Electrical Theory," second edition (1913), Chapters IX and X.

Section 40

THE GAMUT OF ELECTRICAL WAVES

When a beam of white light, such as ordinary sunlight, is passed through a glass prism it is broken up into the so-called *prismatic colors*, which are arranged in the order

of their wave-length. The shortest waves are represented by the violet light, and the longest by the red. The wave-length of the latter is about twice that of the former.

The arrangement of the colors in the spectrum produced by a prism is not such that the distance of each color from the end of the spectrum is proportional to its wave-length. This relationship does hold, however, in what is called a "normal" spectrum. If a spectrum of this latter sort about a yard long could be extended so as to include all known electro-magnetic radiations (among them the Hertzian waves) it would become over five million miles in length.

Of those waves which are shorter than light, the most familiar are the so-called "ultra-violet" waves, which lie just beyond the violet end of the spectrum, and the "X rays," which recent experiments indicate to be different from ordinary light chiefly in the possession of an extremely short wave, or "kink" (see Section 37), about one thousandth that of ultra-violet light. With the "X rays" we have to include the so-called "gamma rays" from radium (see Part I). The existence of these rays can be detected by their chemical effects, for example by their power to produce pictures or shadows on a photographic plate.

The waves which are longer than light comprise the so-called "heat rays," which affect our temperature sense, and the Hertz waves," which are employed in wireless telegraphy.

All of these waves travel at the same speed in empty space, *viz.*, at the rate of 186,300 miles per second. The length of the shortest visible light wave is about one hundred-thousandth of an inch. The longest Hertzian waves measure over a mile from crest to crest. On ac-

count of the tremendous speed at which light travels — the highest speed known to science, and perhaps the highest possible speed — the rapidity of vibration, or the "frequency" of light as it passes through a fixed point, is extremely great. About eight hundred trillion waves of violet light would pass through such a point in a second. The extreme brevity of the interval of time required for the passage of a single wave of this sort — or for the completion of a single oscillation of the generating electron — may perhaps be realized better when it is said that one eight-hundred-trillionth of a second is a vastly smaller part of a second than a second is of the whole of historic time (*i.e.*, one two-hundred-and-fifty-billionth).

REFERENCES

A very popular account of the properties of light is given in "Light, Visible and Invisible" (1910), by Silvanus P. Thompson.

Section 41

COLOR AND THE ABSORPTION AND REFLECTION OF LIGHT

The "Selective Absorption" of Light. — When light passes through a semi-transparent body it always becomes less intense, on account of the absorption which takes place. If the original light is colorless we generally find that it is more or less colored when it comes out of the body. This is due to the fact that white light is a mixture of lights of many different wave-lengths, and that these lights are not all absorbed in equal proportions.

The reason for this inequality of absorption is to be found in the general explanation of the absorption of

light which is given in Part I. A body absorbs only such light as can produce response in its electrons. If the internal forces (see Section 8) of the molecules of a given body permit the electrons which they contain to respond, to an appreciable extent, only to red light, a beam of white light passing through such a body will be colored blue-green, because the red light is removed by absorption and its complementary — blue-green — is thus left unbalanced. Generally a body will strongly absorb light of several quite different wave-lengths.

The Sensations of Color. — The basis of the sensations of color is not to be looked for in the nature of light, so much as in the nature of the effects which light produces in the retina of the eye and in the nerves which are connected thereto. Physics as such offers no explanation of the fact that light of one wave-length gives us a sensation quality almost wholly different from that produced by light of another wave-length. Neither does it account for the fact that a mixture of lights of many different wave-lengths gives white. These are problems in physiology although their solution is, of course, closely connected with the physics of light.

How Color is Produced by Reflection. — When light is colored by *reflection* from the surface of a body, as for example, from a piece of green paper, we must suppose the process to be in reality an absorption phenomenon, since most of the light undoubtedly penetrates the body to a certain extent before it is reflected. It thus passes through a portion of the body in two directions, and during this passage is subjected to the ordinary conditions of absorption.

Bodies differ in their power to reflect light, primarily on account of the fact that the electrons which they contain are not similarly conditioned by their surround-

ings. The best reflectors will in general be the metals, since these contain free electrons in large numbers.

REFERENCES

For a semi-popular discussion of color and absorption, refer to "Light" by R. C. Maclaurin, Chapters II and III. See also Franklin and MacNutt's "Light and Sound" (1909), especially Chapter X.

A very recent and comprehensive exposition of color problems is that of M. Luckiesh, "Color and Its Applications (1915).

Section 42

THE REFRACTION OF LIGHT

How Columns of Light are Bent. — Light may be thought of as moving in columns or "pencils" the fronts of which are perpendicular to the direction of motion of the light. When the front of a column strikes the surface of a transparent body the edge which meets the surface first must be retarded in its motion if, as is generally the case, light moves slower in the body than it does in empty space. Hence, the edge in question falls behind the other parts of the front and the plane of the front is rotated. Since in general the column will move in a direction at right angles to the plane of the front, the light is bent at the surface of the body. If the column of light strikes the surface at right angles there will be no bending because all parts of the front will hit the surface at the same time. The more acute the angle of impact, the greater will be the bending.

This bending of a light column or pencil when it passes through a surface obliquely is called *refraction.* As is well known, refraction lies at the basis of the effects pro-

duced by all lenses and prisms. To explain the details of the process is beyond the scope of this book, since they are complicated and do not depend in any especially significant way upon the modern theory of matter, but it should be noted that refraction depends solely on the fact that the velocity of light is different inside and outside of the medium in question.

"*Dispersion.*" — The same substance refracts light waves of different lengths to different extents. This produces what is known as *dispersion*, a process upon which the formation of spectra by prisms is based. It has been shown experimentally that the degree in which a given substance refracts light of any specified vibration period is closely related with the natural period of vibration of the molecules of the refracting substance itself. As the vibration period of the transmitted light approaches that of the substance, the refraction increases enormously, and then changes suddenly. It is this difference in the refractive power of a single substance for different wave-lengths which makes possible the "dispersion" of color, as in the ordinary prismatic spectrum.

"*Dielectric Capacity*" *and the* "*Index of Refraction.*" — The degree to which a substance refracts light of specified wave-length is called its *index of refraction* for this light, and it has been shown that a definite relationship exists between the *dielectric capacity* of a substance and its index of refraction. (See Section 33 for another connection of dielectric capacity.) For many solids and liquids this relationship is a complicated one when the frequency of the light considered is close to that of the molecules of the substance itself. However, in the case of gases, and if sufficiently long waves are used, for all bodies, the refractive index is found to be proportional to the square-root of the dielectric capacity.

The dielectric capacity of a body measures the ease with which the electrical components of its molecules undergo temporary separation (without decomposition of the molecule) through the activity of outside electrical forces. In general, the more the particles of a substance respond to the force of a light wave the greater is the effect upon the speed of the wave. Hence it is easy to see why, within the above-mentioned limits, a substance which has a high dielectric capacity should also have in general a high index of refraction.

Both refraction and absorption occur to the greatest extent when the frequency of the light which is passing through a body most closely approximates the natural frequency of vibration of the molecules of the substance, since under these conditions the response of these molecules is the greatest possible.

REFERENCES

On refraction and reflection, consult R. C. Maclaurin's "Light," Chapter VI.

Section 43

ROWLAND'S EXPERIMENT

The fact that a magnetic field is produced by the motion of an electrically charged body was proven by the late Professor Rowland of Johns Hopkins University.

Professor Rowland's experiment was a very simple one. Everybody is familiar with the fact that the presence of a magnetic force can always be detected by the deflection which it causes in the position of a compass needle. Some strips of gold-leaf were cemented upon a hard rubber disk, and after they had been charged with electricity the disk was rotated very rapidly. The needle of

a delicate compass placed near by showed a distinct deflection, which could only be ascribed to the magnetic forces generated by the motion of the charged strips of gold-leaf.

The relation between the direction of the magnetic forces and that of the moving electricity or electric current is shown in Figure 26.

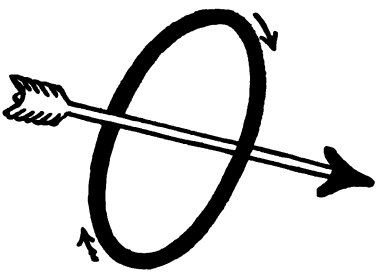


Fig. 26

THE DIRECTION OF THE MAGNETIC FORCES ABOUT A MOVING ELECTRICAL CHARGE

Magnetic forces exist around every moving electrical charge. If the charge is positive and is moving in the direction of the large arrow the magnetic forces will possess the arrangement and direction indicated by the black circle and its small arrows. If the charge is negative it must move in the opposite direction to produce the same magnetic effect.

REFERENCES

On the relation between electricity and magnetism, see Oliver Lodge's "Modern Views of Electricity," Chapter VII.

Section 44

THE DEFLECTION OF MOVING ELECTRONS BY A MAGNET

The principle which is employed in the dynamo for the generation of the electrical current is illustrated in certain modern experiments and observations to which we have already referred in several places.

VI этаж

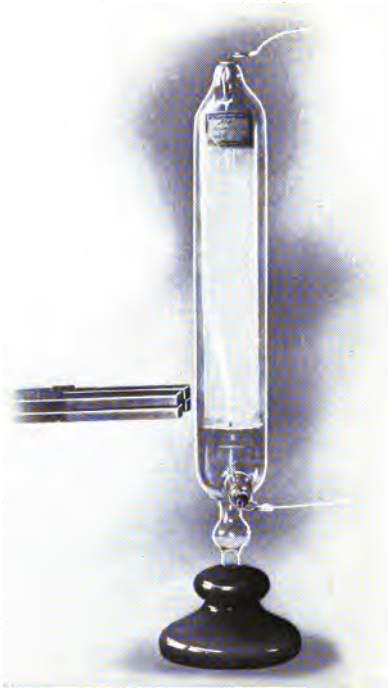
ТЕНЗАМ А УА ВЗА ЗЛАЧОНТАЛ ОЭ ЯОТЕТЕЛЕ ЯНТ

Тип фотоэлектронного прибора: вакуумный, с внешним фотоэффектом. Принцип действия прибора основан на явлении внешнего фотоэффекта. Под действием падающего на фотокатод светового потока с поверхности катода вылетают электроны, которые ускоряются электрическим полем и попадают на анод. Анодный ток, возникающий при этом, усиливается и регистрируется измерительным прибором. Чем больше световой поток, падающий на фотокатод, тем больше анодный ток.

Plate IV

THE DEFLECTION OF CATHODE RAYS BY A MAGNET

The photograph on the left shows the normal cathode discharge, in the absence of a magnetic field. The photograph on the right shows the same discharge deflected under the influence of a permanent magnet, which has been brought near the tube. The white screen in the tube is made of fluorescent material, so as to show clearly the impact of the rays, and is tipped, slightly, towards the observer.



In Section 25 we have mentioned the fact that the so-called cathode rays, which in reality consist of very rapidly moving electrons, are capable of being deflected by a magnet. Where the rays impinge upon the walls of the "vacuum tube" in which they are produced they cause a bright spot of light. If a strong magnet is brought near the tube this spot of light is seen to move.

This deflection of the rapidly moving charges in the cathode rays has been very carefully studied and the results embodied in what is believed to be one of the most fundamental and exact of electromagnetic laws; — "The Law of the Deflection of Moving Charges in a Magnetic Field."

REFERENCES

See J. J. Thomson's "The Discharge of Electricity Through Gases" (1898), Chapter on the "Cathode Rays," p. 137; and Oliver Lodge's "Electrons" (1906), Chapters VIII–XIX inclusive.

Section 45

ALL BODIES ARE MAGNETIC

Dia- and Para-magnetism. — One ordinarily thinks of the vast majority of substances as "non-magnetic." Iron and steel seem to be marked out from other bodies by their possession of magnetic powers. As a matter of fact, however, every known substance possesses magnetic properties.

There are two kinds of magnetism, dia- and para-magnetism. When a dia-magnetic body is placed in the field of a strong magnet its long axis tends to turn so as to be at right-angles to the direction of the lines of magnetic force. Para-magnetic bodies, on the other hand, tend to place their long axes *parallel* to their lines of force.

The fact that all bodies have magnetic properties indicates from the present point of view that *they all contain electrons in motion.* Whether a particular body is dia- or para-magnetic probably depends upon the exact way in which the electrons are moving and upon the conditions which limit this motion.

Permanent Magnetism. — Iron, cobalt and nickel differ from other substances in their power to acquire strong *permanent magnetism.* This property may be explained in the following manner. If there are electrons rotating within or about the atoms of a substance, each atom will behave like a very small magnet. But in a visible body there would be so many of these minute magnets with their positive and negative poles pointing "every which way" that the resulting outside effect would be practically nil.

In order that such an external effect should be produced it would be necessary for a number of the little magnets to point in the same general direction, so that the individual influences would be added to, instead of neutralizing, each other. To bring the atoms into line in this way an outside magnetic force might be applied, for it is known from experiments with a compass needle that one magnet can cause another to turn upon its axis. It is probably some such reaction of the atomic magnets as this which produces all of the phenomena of dia- and para-magnetism. In the majority of bodies the atoms do not remain in magnetic line when the outside force is removed. But in others they do tend to remain in line and these latter are said to possess permanent magnetism.

If magnetization actually does involve a turning of the molecules on their axes, we should anticipate that a certain amount of the energy which is used in the process

might be converted into heat, since additional motion is imparted to the molecules. This effect can actually be observed in the case of the more magnetic substances, and is at the basis of a troublesome loss of energy in dynamo work technically called "hysteresis."

REFERENCES

An exhaustive discussion of "Magnetism" by Shelford Bidwell will be found in the eleventh edition of the "Encyclopaedia Britannica." For a simple and briefer account see Norman Campbell, *loc. cit.*, Chapter V.

Section 46

RADIO-ACTIVE SUBSTANCES

The Discovery of the Radio-Elements. — The first substance found to be radio-active was uranium. The discovery was made by Becquerel in 1896. M. and Mme. Curie, however, soon found that the ore from which uranium was extracted was four times as radio-active as pure uranium itself, and this observation led to the discovery of radium, a new chemical element having a radio-activity over a million times greater than that of uranium. Later on the same investigators laid bare further and even more powerful radio-active bodies: polonium and actinium. Another element, thorium, already known to chemists, was found by Schmidt to be radio-active to about the same extent as uranium.

"*Disintegration Series.*" — A complete list of the radio-active elements is given in Table II of Section 5. Most of the substances named in this table are what may be called "radio-active products," that is, they are bodies which are produced in the course of radio-activity. Radium, for example, apparently breaks up into helium and "niton," both of which are gases. The emanation

(niton) decomposes, in turn, forming a solid substance, *radium A*, which is soon converted by a similar change into *radium B*, and so on. It is supposed that the final product of this series of changes is chemically identical with lead.

Similar "disintegration series" of substances are derived from uranium, thorium, and actinium, as shown in the table (II, Section 5). A series may "branch" at certain points. It is now believed that both radium and actinium are ultimately derived from uranium, by such a process.

Besides these special radio-active bodies others have now been shown to possess slight radio-active powers. Many investigators believe that all substances are somewhat radio-active, but it is not yet entirely certain whether the faint activity which exists, is an intrinsic property of the substances or whether it is to be ascribed to the presence within them of small traces of the radio-active bodies proper.

The Law of Decay of Radio-Active Substances. — As stated in Part I, the rate of decay of a radio-element, so far as yet found, is independent of all external conditions. The law of this decay is that, for a given element, the same fraction of any specific volume will always break up in the same period of time. Thus, if we should start with an ounce of radium A, it would be half gone at the end of three minutes. In three minutes more one-half of the remainder — or one-quarter of the original amount, in addition — would have broken up, and so on. It is clear that a law of change of this sort would theoretically never lead to the total disintegration of any given quantity of the substance, however small. This is why the "life" of a radio-element is stated in terms of the time required for one-half of a given amount of it to decay.

These "half-times" vary from about twenty-six billion years in the case of thorium to only one ten-billionth of a second in the case of radium C′. The intensity of the radiation from any radio-active substance is naturally inversely proportional to the time required for a quantity of it to decompose. It has been shown by Geiger and Nuttall that the shorter the period of life of a radio-element the faster its alpha particles move. There is a similar relationship for the beta particles.

The Position of the Radio-Elements in the Periodic Table. — The position of the principal radio-active elements in the periodic table is especially worthy of notice. It will be seen (Section 6) that not only are they among the heaviest of the elements, but that all of the heaviest elements are radio-active. Apparently the relative instability of the radio-elements is a corollary of complexity of internal structure, and is analogous to the unstable character of the higher chemical complexes, such as the organic compounds of which living bodies are made up. However, mere weight is not the only factor involved, since uranium, the heaviest element known, and the parent of the majority of the radio-active substances, is one of the least active of them all. It is estimated that the time of decay of uranium is long compared with the age of many of the minerals in which it is found. If it were not for this fact, and the similarly low activity of thorium, all signs of radio-activity would have disappeared from the earth long ago. It is probable that other series of radio-elements, perhaps of even greater atomic weight, have existed in the past, but have left no recognizable traces behind them.

REFERENCES

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C. W. Raffety: "An Introduction to the Science of Radio-Activity" (1909).

A. T. Cameron: "Radio-Chemistry," (1910).

Section 47

HOW THE RAYS FROM RADIUM ARE STUDIED

We have seen in Part I and in Section 25 that moving electrically charged bodies can be turned from their straight-line paths, or deflected, by the action of a magnet. Hence it is possible to get a first indication as to which, if any, of the rays from radium are electrical particles, and which are electrical waves, by placing a magnet across their paths. The first type of rays will be deflected while the second will not. The extent to which they are deflected, when combined with certain other measurements which have been mentioned in Section 25, shows the speed at which they are travelling, as well as the sign of their charge and the ratio of this charge to their mass.

When an experiment of this sort is tried upon a bundle of rays from radium, certain of the rays are found to be uninfluenced and to move on in a straight line as before. Another set is deflected slightly, while a third suffers very marked change in path. The last two are diverted in opposite directions, which proves their charges to be positive and negative respectively. The first type of rays are the "gamma rays," the second the "alpha rays," and the third the "beta rays." The methods which are used in measuring the speeds, charges and

masses of the alpha and beta particles are similar to those described in Section 25 for the "cathode rays."

The fact that the beta particles can penetrate even thick pieces of solid matter is proven by simply directing a pencil of beta rays towards a plate composed of the solid substance in question, and noticing that the rays appear in a somewhat diffused and attenuated state on the other side of the plate.

As already mentioned, C. T. R. Wilson has devised a method by means of which it is possible to photograph the paths of single alpha particles in their motion through a gas.

REFERENCES

The methods employed in the study of radio-activity are popularly discussed by R. K. Duncan in his "New Knowledge" (1908), Part IV.

Section 48

HOW RUTHERFORD PROVED THE ALPHA RAYS TO BE HELIUM ATOMS

The fact that the alpha rays are atoms of helium was proved in a very striking and simple experiment by Ernest Rutherford. Helium is a gas, and it is a well-known fact that every gas when subjected to the action of an electrical discharge gives off light of a peculiar color, which can be split up by a glass prism into the so-called "spectrum" of the gaseous substance (see Section 39). Rutherford very carefully removed all traces of helium from a large glass tube and then placed within this tube a smaller one of very thin walls containing gaseous helium. After permitting the apparatus to stand for several days he passed an electrical discharge through the larger tube, and examined the light to see if the spectrum of helium was present. He found it to be absent, showing that ordinary

helium could not pass through the walls of the smaller tube.

He now replaced this latter tube by an identical one containing not helium but radium emanation, which is constantly throwing off alpha rays. Since the walls of the tube were thin the great speed and energy of the particles in the rays enabled them to penetrate the walls and enter the atmosphere of the larger vessel.

After the apparatus had stood under these conditions for a period of time Rutherford again passed an electrical discharge through it, and found that it distinctly showed the spectrum of helium. This seems to be conclusive proof that the alpha ray particles are actually atoms of helium.

The mass or weight of the alpha particles has also been measured and has been shown to be of a magnitude in harmony with this conclusion.

REFERENCES

See Rutherford's "Radio-Active Substances and their Radiation" (1913), pp. 137–140 and Chapter XVII.

Section 49

THE NATURE OF THE GAMMA RAYS

We have seen in Section 37 that electrical waves can be regarded as kinks in lines of electrical force which are produced whenever the velocity of motion of an electrically charged particle is altered. Now we know that the beta particles bear electrical charges, and that they are suddenly emitted from the atoms of radio-active substances at a tremendous speed. In accordance with the theory, then, they ought to give rise to electrical waves of very high frequency, that is, the kinks which are pro-

duced in their lines of force should be exceedingly sharp. This conclusion seems to harmonize with what we know about the gamma rays, which are apparently made up of the electrical waves in question.

When the beta particles are stopped in their headlong flight by striking the atoms of some other substance we should expect further gamma (or X) rays to be produced, because any change in the velocity of one of these particles should give rise to an electrical wave, whether the change be of the nature of an acceleration or a retardation. It has been found by experiment that such rays are actually produced under the circumstances specified. They belong to the class of "secondary rays" in which, also, must be included the further beta radiation which is set up by the gamma rays themselves when they are absorbed by material bodies.

Another type of secondary rays produced under entirely analogous conditions and probably of the same general nature are the well-known "X rays." Certain very recent experiments which prove beyond a doubt that the latter, and probably also the gamma rays, are not moving material or electrical particles, in the usual sense, will be discussed in Section 55. In that place, also, will be considered the explanation of the great power of gamma and X rays to penetrate bodies opaque to ordinary light.

REFERENCES

Concerning the gamma rays, see R. K. Duncan's "The New Knowledge" (1908), pp. 109–112. Also Norman Campbell's "Modern Electrical Theory," second edition (1913), pp. 273 *ff.*

Section 50

THE ENERGY OF THE ATOM

The enormous energy of the inner constitution of the atom is probably very closely connected with the great stability of atoms in general. Even the atoms of radium are only relatively unstable, since if we consider any single radium atom it has what we might call an "expectation of life" of several thousand years. The great stability of the atom is due to the fact that the forces which hold the parts of the atom together are very great, and the magnitude of these forces is closely associated with that of the intra-atomic energy.

We have several times spoken of the forces of chemical affinity and cohesion as *residual* in character, as representing the attractions which are, so to speak, "left over" after the parts of the atom have been cemented together. If chemical energy (for example) is a residue of the intra-atomic energies we should expect it to be relatively much smaller than these energies, just as the stability of the molecule is relatively much less than that of the atom. We have become accustomed to the quantities of energy liberated in chemical changes and have taken them as standards, so that when we come to consider the primary energies of the atoms these seem unbelievably great.

REFERENCES

Concerning intra-atomic energies read R. K. Duncan "The New Knowledge," Part 5, Chapter III. The energy liberated in radio-activity is discussed by J. J. Thomson in his "Electricity and Matter" (1904), pp. 152 *ff.*

Section 51

THE RADIO-ACTIVITY OF POTASSIUM

As nearly everyone knows, the element potassium is a constituent of ordinary caustic potash. Yet this common element has been shown by Norman Campbell to be definitely radio-active. The rays which it emits appear to be principally of the "beta" type, the intensity of the rays from potassium being about one one-thousandth that of the beta rays from uranium. All of the potassium salts are radio-active, and thus far no evidence has been adduced to show that this activity is due to impurities.

Other of the so-called alkali metals, for example rubidium, have been shown to possess slight radio-activity.

REFERENCES

See Norman Campbell: "The Radio-Activity of Potassium" in the Proceedings of the Cambridge (Eng.) Philosophical Society for 1908, Vol. 14, pp. 557–567. Also Campbell's "Modern Electrical Theory," second edition (1913), pp. 187–188.

Section 52

INORGANIC EVOLUTION

We have seen in Section 39 that all of the elements possess characteristic "spectra" which consist of series of lines. For most elements these series are quite complex and the positions of the separate lines in the spectrum, that is, the wave-lengths of the lights which compose them, do not change. However, the exact number of lines which are present depends to a certain extent upon the conditions under which the element is made luminous. The spectrum from a flame has fewer lines than that from an electric arc.

Now astronomic observations have shown that in the

light from many stars the spectra of certain elements are curiously incomplete. In general, the hotter a star is the more incomplete the spectra of its elements appear. If we suppose that the different sets of lines in the spectrum of the element are produced by the vibrations of different electrons, or systems of electrons, within the atom, it is natural to infer that the simplification of the spectra in the hottest stars stands for an actual breaking up of the atoms in these stars.

But in addition to this it has been shown, by Sir Norman Lockyer on the basis of spectroscopic evidence, that in the very hottest stars are to be found only the simplest elements, such as hydrogen, helium, etc., along with partly formed elements of higher atomic weight. The cooler a star is the more elements it contains, and the higher are the atomic weights of these elements.

These facts suggest that the elements are undergoing an actual evolution in certain of the heavenly bodies, an evolution which depends primarily upon the fact that these bodies are passing through a process of cooling. The lightest and simplest elements are formed first, and after them the heavier and more complex ones. Among the latter are the radio-active substances.

REFERENCES

Sir Norman Lockyer's own account will be found in his "Inorganic Evolution, as Studied by Spectrum Analysis." A simpler presentation of the facts is given by R. K. Duncan in Part VI of "The New Knowledge" (1908).

Section 53

THEORIES OF THE STRUCTURE OF THE ATOM

Thomson's Theory.—Up to very recent times the most promising conception of atomic structure was that elaborated by Sir J. J. Thomson in a highly mathematical

paper published in the English *Philosophical Magazine*, in 1904. Although it is practically certain that the theory, as originally stated, is not accurately true, it must nevertheless be admitted that no other view has appeared which gives us an equal feeling of insight into the mystery of the chemical elements.

On the basis of the known laws of electrical attraction, Thomson calculated the constitution of the series of hypothetical atoms which would be generated by the successive addition of electrons to a large sphere of positive electricity always of sufficient charge to just neutralize the electrons. For simplicity, he assumed the electrons to be concentrated in a single plane. He was able to show that the electrons would arrange themselves into rings and that with an increase in the total number there would be a periodically recurring tendency for fresh rings to be formed, in addition to those already present. However, the latter, also, would be obliged, from time to time, to increase their electronic contents in order to maintain the stability of the system.

With the formation and development of each new ring the properties of the atoms might be expected to repeat to a limited extent, those which were passed through in the development of the previously formed ring. The presence of the latter — owing to the general modification of the forces of the system which it would involve — would preclude an exact repetition of properties. It is clear that a very close analogy exists between this theoretical series of atoms of Thomson's and the actual system of the elements, as revealed in the periodic table. The first member in each "period" in the table (see Section 6) may be supposed to coincide with the formation of a new ring, which would contain, in the given element, only one electron.

As stated in Part I, the recent "nucleus theory" of the structure of the atom supposes that the positive electricity, instead of forming a large sphere, coextensive with the general volume of the atom, is concentrated in a very minute central region. However, we still hear of concentric rings, or shells, of electrons surrounding this nucleus, and it is probable that, in a general way, the arrangement of the electrons resembles that in the Thomsonian atom.

The Nucleus Theory. — The "nucleus theory" was proposed by Rutherford to explain the manner in which the alpha rays from radio-active substances are scattered as a result of their passage through material bodies. This scattering may be supposed to be caused by the action of the intrinsic forces of the atoms of the body upon the charged particles which make up the rays. The degree of scattering is measured by the angle made by the path of the ray as it leaves the thin sheet of substance, through which it has passed, and its original line of travel. Now experiment shows that even when the average degree of scattering is relatively low, a small fraction of the rays are turned through a very large angle, often so that their motion is actually reversed in direction.

Since the original speed of the alpha particles and their charge are known, it is possible to calculate what conditions would be necessary to cause a deflection of this magnitude. In the case of the element gold, such calculations show that the positive electricity of the atom must be concentrated on a sphere about one trillionth of an inch in diameter, which is only one ten-thousandth part of the diameter of the atom itself.

It is estimated that in passing through hydrogen gas, some of the alpha ray particles come within one twenty-five-trillionth of an inch of the centers of the positive

nuclei. Since this is less than the diameter of an electron it seems probable that the bare positive nucleus is smaller than are the negative particles in the atom. In Section 25 we have seen that on the assumption that the electron is made of pure negative electricity, it is possible from a knowledge of its mass and charge to calculate its size. Now, the facts indicate that the mass (or weight) of the positive component of the atom is enormously greater than that of the electron, so much so that it is practically equivalent to the total weight of the atom. On this basis, calculation shows that the nucleus of the hydrogen atom — if its mass is wholly electrical — must have a diameter of about one ten-quadrillionth of an inch, or one eighteen-hundredth that of the electron. This result appears to be in harmony with that reached by the study of the alpha-ray scattering.

The supposition that the positive components of the nucleus of most atoms have electrons closely bound up with them is necessitated by the facts of radio-activity. The tremendous speed with which the electrons of the beta rays are sent off, demands original intra-atomic forces which could only result from an exceedingly close packing together of the atomic parts which are involved. Moreover, there seems little room for doubt that there are at least two classes of electrons in the atom, (1) those which directly determine its physical or chemical properties, and a fraction of which can be separated from the atom and replaced again without great difficulty, and (2) those which leave the atom only during a radio-active change, and the loss of which means an apparently irrevocable alteration in the fundamental nature of the element.

It seems probable, however, that electron groups of varying degrees of superficiality, so to speak, exist within

complex atoms. These may be thought of as corresponding with the successive rings of the Thomsonian atom. The most superficial system of all is that of the so-called valency electrons, which are probably responsible for the more obvious chemical properties of the substance and, as Stark believes, for its band spectra. Still deeper electron layers give rise to the recently discovered X ray spectra (see Section 55).

The Number of Electrons in the Atom. — Numerous attempts have been made to calculate the number of electrons in the atoms of the various elements. This can be done on the basis of the degree in which rays of several sorts are scattered in passing through sheets of the elements in question. The more electrons there are — that is, obstacles for the rays to encounter — the more scattering will occur. Results obtained by a number of different methods indicated that the number of electrons is approximately equal to one-half the atomic weight. But it is clear that if, as in the case of hydrogen, one unit of positive charge is always associated with one unit of weight, the number of electrons in the atom would have to be accurately equal to the atomic weight in order to balance the charge of the nucleus. We are led, therefore, to suppose that there are as many electrons bound up in the nucleus as there are in the body of the atom. The number of these latter, "external" electrons is controlled by the magnitude of the unbalanced charge of the nucleus, which is represented by the "atomic number" (*vide infra*). As a matter of fact, as an examination of Table I, Section 5, will show, the nuclei of the heavier elements must contain *more* electrons than the body of the atom.

Isotopism. — Radio-activity, as we have stated, is indubitably an affair of the nucleus, and it appears to

depend upon the ejection either of a doubly, positively, charged helium atom — alpha particle — or a singly, negatively, charged electron — beta particle. It is obvious that if the nucleus loses one alpha particle and then two electrons its resultant charge will be the same as before these three radio-active changes had occurred. Consequently, the number and arrangement of its external electrons will be the same as before the change, and the two elements, although differing in atomic weight by four units, will have identical chemical and physical properties. As shown in Table II, Section 5, many such so-called *isotopes* have been demonstrated among the radio-active elements. A mixture of isotopes acts like — and indeed is — a chemically pure substance, and there is no chemical reaction which can be used to separate its components. However, these components can easily be distinguished from each other by radio-active tests. Chemical tests distinguish between only ten kinds of radio-elements, whereas radio-active tests show thirty-four or more.

Atomic Numbers. — The expulsion of an alpha particle from an atom causes the corresponding element to move two places from right to left in the periodic table (see Section 6); the loss of a beta particle reverses this movement one place. It appears, then, that the position of an element in the table depends not upon its atomic weight, directly, but upon the resultant positive charge of its nucleus, — which is called its *atomic number*, — and the successive places in the table correspond with unit differences in this charge. Consequently, in so far as the table is regarded as a chemical schema, its principle should be restated as follows: "All of the chemical properties of the elements are periodic functions of their atomic numbers (instead of weights)." Chemical analysis, it

would appear, is really an analysis of matter only into different types, not into different elements.

The recent discovery of a means of measuring the wave-lengths of X rays has shown that all of the elements, under the right conditions, give off X rays, the lengths of which are characteristic of the element in question. It has been found possible to calculate these wave-lengths by means of a very simple formula involving the atomic number or, *vice versa*, to deduce the atomic number from the wave-length. Measurements of this sort by Moseley indicate that the atomic number of gold is 79, and that from aluminium to gold, in the periodic table, only three possible elements are missing. The atomic number of the heaviest element, uranium, appears to be 92, although there is some disagreement concerning this point. If this is correct and if uranium is the heaviest element which can exist, then it means that only 92 different chemical elements are possible.

The Hydrogen Atom. — In some respects hydrogen occupies a unique position in the system of the elements. The alpha ray particle, which is a helium atom with a double positive charge, may be thought of as consisting of the helium nucleus stripped of its external electrons. The ordinary hydrogen *ion*, bearing one positive charge, is probably the bare nucleus of the hydrogen atom. However, the alpha particle contains four units of weight to two of charge, while the hydrogen ion has one unit of weight to one of charge. On the basis of the argument previously presented it would appear that while the helium nucleus has bound up with it two electrons, the hydrogen nucleus, or ion, consists of pure positive electricity, and is, in fact, a positive electron.

On the supposition that the uncharged hydrogen atom is thus made up of two electrical particles, one positive

and the other negative, the Dutch physicist, Bohr, has shown that by use of the known electro-magnetic laws and the new "quantum" theory of light (see Section 54), some very remarkable conclusions can be reached. For a long time it has been known that the position of the "lines" in the hydrogen spectrum can be calculated with amazing exactness by means of a certain mathematical formula (named after its discoverer, Balmer) which had been arrived at empirically by a method of trial and error. Up to the recent work of Bohr, however, it seemed impossible to derive this formula by means of the laws of simple mechanics and electricity from any conceivable hypothesis about the structure of an atom, especially from a simple one. But by introducing the assumptions of the new theory of light, Bohr has shown that the formula in question follows very simply from the conception of the hydrogen atom above described. This result can hardly be considered other than epoch-making in the history of atomic and optical theory.

Bohr's theory disposes of a difficulty which has bothered physicists for some time, *viz.*, the problem as to why the electrons within the atom continue to rotate about the center of attraction, instead of rapidly falling into it. Centrifugal force would keep them out as long as they maintained their speeds, but the ordinary laws of radiation demand that these speeds should constantly diminish, owing to the continuous emission of energy in the form of electrical waves. However, the quantum theory necessitates that such emission should occur only in discontinuous units of fixed magnitude. Consequently, it would be impossible for the electron to drop gradually into the atom; it would be obliged to fall in steps or jerks. Each jerk would generate a characteristic wave, corresponding with a definite line in the spectrum of the ele-

ment — it being consistent with the facts to suppose that line spectra are formed only when electrons are separated from or returned to a definite place in the atom. When the electron has completed any drop and radiated the corresponding energy it remains in equilibrium, probably rotating about the nucleus, but no longer radiating.

It is difficult to handle mathematically the problems connected with the exact structure of atoms more complex than that of hydrogen, but it seems probable that these atoms are made up of larger numbers of positive particles, and electrons, rotating in more complex ways. It is apparent that there is a close analogy between the structure and internal processes of atoms, as conceived in modern theory, and those of astronomic systems. This is why the type of atom above considered is sometimes characterized as the "Saturnian atom."

REFERENCES

J. J. Thomson's theory of atomic structure is well summarized in popular form by R. K. Duncan in "The New Knowledge" (1908), Part 5, Chapter II. Thomson's own account appears in popular form in his "Electricity and Matter" (1904), Chapter V.

See also Norman Campbell's "Modern Electrical Theory," Second edition (1913), Chapter XIII. Bohr's articles are in the *Philosophical Magazine* for July, September, and November, 1913, Vol. 26, pp. 1, 476 and 857. J. J. Thomson's latest theory will be found in the same journal for October, 1913, p. 792.

On isotopes see Frederick Soddy's "The Chemistry of the Radio-Elements" (1915), Part II. On atomic numbers and the Bohr atom: W. H. and W. L. Bragg's "X Rays and Crystal Structure" (1915), pp. 77 to 87.

Section 54

THE QUANTUM THEORY OF RADIANT ENERGY

The Nature of the Theory. — When light travels from one part of space to another there is a motion of a certain

amount of "radiant energy" through the intervening distance, and at any time during the motion this energy must be localized in a definite region of space. The question as to whether radiant energy is or is not *atomic* may consequently be asked in the following way. Is light energy travelling in free space spread out uniformly and continuously in that space, or is it concentrated in a limited number of relatively small and clearly defined regions, the amount and intensity of the energy in each of these regions being invariable for a given kind of light?

The first alternative is the one which had been accepted up to quite recent times. It assumed that radiant energy can be emitted from bodies continuously, in any amount and at any intensity, that it spreads out uniformly from its source like a perfect non-molecular fluid, becoming steadily weaker the further it goes from the source, according to the well-known "law of inverse squares." The second alternative, which corresponds to the modern doctrine of light "quanta," denies all of these assumptions. It states that light is not radiated from bodies continuously, but instead in sudden outbursts, each of which is of definite magnitude and intensity determined only by its wave-length or frequency. It would be impossible for a body to radiate a fraction of one of these units, so that quantities of radiation which are not integral multiples of the units in question cannot exist.

Moreover, the intensity of one of these light atoms, or quanta, does not decrease with its distance from the source, and consequently it does not spread out as it travels. The reason that light seems to fall off in intensity with distance lies in the fact that the *number* of light atoms to be encountered in a given region of space naturally becomes less the farther that region is from the emit-

ting body. This conception of the structure of a beam of light means that all optical images are really built up on the same principle as the ordinary "half-tone" engraving, that is, they are made of minute dottings or stipplings far too small to be detected by the eye. (However, the sensitiveness of the retina is so great that a visual sensation can be produced by relatively few quanta of the right kind of light.)

Such a striking alteration as this in the theory of light cannot be without strong grounds. In discussing these, no attempt will be made to follow the order of their historical appearance in connection with the problem.

The Photo-Electric Effect. — We have seen in Chapter V, that many solid bodies, especially metals, under the influence of high temperatures, give off electrons. It has been found that they also can be made to emit electrons at ordinary temperatures if their surfaces are exposed to the action of ultra-violet light or X rays. If we are not to assume that the metal becomes radio-active under the action of the light, we must suppose that the energy of motion of these emitted electrons comes from the light itself. The very curious fact now appears that this energy — that is, the highest speed with which any of the electrons travel — is independent of the intensity of the light which shines upon the surface. If the light is weak, relatively only a few electrons are given off, but those which do appear have the same velocity which is characteristic of the effect with lights of higher intensity. These results seem to be compatible only with some such notion of the atomic structure of light as we have just outlined.

Measurements upon the speeds of the electrons in the photo-electric effect — as the phenomenon is called — prove that their energy of motion, although independent

of the intensity, is closely proportional to the "frequency" of the rays employed, that is, the shorter the "wave-length" of the radiation the faster the emitted electrons move. This connection between "frequency" and energy is one of the fundamental principles of the quantum theory; it resolves itself ultimately into the statement that the energy of any light quantum is directly proportional to its frequency. The higher the frequency the higher the energy, but for a given frequency the energy is fixed and invariable.

If this principle is valid, it is clear that it should be impossible to generate quanta of high frequency from those of low frequency, since this would contradict the law of the conservation of energy. In accordance with this, it has been shown experimentally that when one kind of radiation is changed into another — as, for example, "fluoresence" and "phosphorescence" — the alteration in wave-lengths is, in most cases, from high to low frequency. This empirical principle is known as *Stokes' law*. It holds for the transformation of X rays, as well as for those of ordinary light.

Such transformations as these must always be accomplished by permitting the light to fall upon some material body, and there is practically no doubt that the active factors in the change are the electrons which are bound up in the atoms of the body. Experiment makes it probable that all such electrons have *natural rates of vibration*, which depend upon the constitution of the atoms or molecules of which they form parts. The photo-electric effect and its analogues in all probability depend upon the ejection of electrons from atoms under the influence of the electrical forces in the light ray. The quantum theory, however, makes it seem probable that (1) the energy of the light cannot be transferred to the electron unless the

frequency of the light is at least approximately the same as that natural for the electron itself, and (2) if the electron takes up any of the energy of the light quantum it must take it all. In harmony with this view it is found that so far as present measurements permit us to judge, the energy of the electrons emitted under the action of light and X rays is the same as that of the respective light quanta.

Other Facts Underlying the Theory. — There are further important results of the idea that an electron, atom, or molecule can take on or part with only whole light quanta, and only such quanta as have approximately their own natural frequencies. For example, it can be shown theoretically, upon certain reasonable assumptions with regard to the molecular conditions underlying the facts of specific heat, that if the quantum theory is true the specific heats of all substances at or near absolute zero, should themselves be very close to zero. At low temperatures the average energy of vibration of the atoms is so small that only a few of them are able to retain whole quanta of energy, and if they are unable to retain whole quanta they cannot have any energy at all. Consequently, at low temperatures the atoms of a body lose their power to absorb heat, and hence the body suffers a radical decline in its specific heat. (See Section 24.) The recent experimental work of Nernst and his co-workers has shown that such changes in the specific heats of bodies actually do occur, and that their manner of occurrence satisfies expectations based upon the quantum theory.

However, probably the most important consideration of all — which is presented at some length in Chapter X, and which, unfortunately, is too involved to be developed much more completely here — is that which first led the

German physicist, Max Planck, to propound the quantum theory. It concerns the manner in which the amounts of light of different wave-lengths emitted by glowing solid bodies at various temperatures are related with the wave-lengths and temperatures in question. This relation is represented in the "curve of distribution" of energy in the spectrum, which has been discussed in Section 39. For any given temperature there is a certain wave-length which has a higher intensity than any other. Wave-lengths greater or less than this have increasingly lower intensities. Various only partially successful attempts had been made by several physicists to explain the exact relations between temperature, wave-length, and intensity in terms of the electron theory of radiation. Planck found that such an explanation could be given if it be assumed that the radiation takes place discontinuously, and that each quantum of light radiated has an energy proportional to its frequency, *i.e.*, inversely proportional to its wave-length. The demonstration of the possibility of such an explanation proved to be of epoch-making importance in theoretical physics.

Significance of the Quantum Theory.—The possible far-reaching significance of these developments in the theory of radiation may perhaps be suggested by a few statements, the whole meaning of which, however, can only be appreciated by one closely acquainted with physical science and its history. In the first place, it has been shown conclusively by the English physicist, Jeans, that although the facts just mentioned as Planck's first basis for the quantum theory demand an atomic view of the nature of radiation, the interpretation given to them makes them wholly inconsistent with the most fundamental principles of the science of mechanics. In other words, it would appear that, to a certain extent at least,

events in the world of atoms and electrons do not follow the laws of ordinary mechanics.

Secondly, it appears that these events do involve in a very definite way certain considerations based upon the theory of probabilities or chance. For some time it has been known that the so-called *second law of thermodynamics*, which states that the amount of available energy in the universe tends constantly to decrease, could be derived from a study of the relative probabilities of given configurations of the molecules composing any group of bodies. Certain arrangements of the molecules are more probable as the outcome of a disturbance than are others. There would always be a tendency for the less probable configurations to be replaced by the more probable ones. This tendency corresponds with the statement that the "entropy" of a given group of bodies tends always to increase; the greater the entropy of the group the less available energy there is in it, the nearer all of energy in the system is to being uniformly distributed heat. This latter state of affairs is the most "probable" of all states of the molecular system, and the "entropy" of the system as a whole is merely another expression for the probability of the particular configuration of molecules or molecular conditions existing within it.

In order that considerations of this sort, involving the doctrine of chance, should be applicable to a subject matter, it is absolutely necessary that this subject matter consist of discrete individuals or particles, in short that it be atomic. Now, it has been shown very decisively that the conception of entropy and the principles of thermodynamics at large are definitely applicable to the behavior of radiant energy, and hence we must almost inevitably conclude that such energy is atomic in nature.

It is of course quite possible that radiant energy is

atomic while other forms of energy are not, that there will be a limit to the application of the principles of atomism to the physical universe. Indeed, certain well-known physicists still hold that even the facts which support the quantum theory of light can be explained without any radical change in our present doctrines. The exact outcome of this contention still rests in the balance.

REFERENCES

A remarkably complete, although somewhat mathematical discussion of the Quantum Theory and its grounds is given by Norman Campbell in his "Modern Electrical Theory," second edition (1913), Chapter X. A somewhat simpler, but also very clear account is that by R. A. Millikan, "Atomic Theories of Radiation," in the journal *Science* for January 24, 1913 (Vol. 37, pp. 119–133). For a popular discussion of the growth of atomic theories in physics see Sir Oliver Lodge's "Continuity" (1914).

Section 55

X RAYS AND THEIR MEASUREMENT

The Origin and Nature of X Rays. — X rays are formed when the cathode rays, of which we have spoken in Section 25, are stopped in their course by striking a solid plate, commonly called the "anti-cathode." Since the electrons of the cathode rays are moving much more slowly than are those of the beta rays (see Section 49), the "kinks" (see Section 37) of which they are made up are not so sharp, but they are nevertheless very much sharper than those of ordinary light.

As mentioned incidentally in Section 53, it has been shown that a fraction of the X rays given off by the anti-cathode have a wave-length and penetrative power which is characteristic of the element of which the anti-cathode is composed. These "characteristic X rays" are of

shorter wave-length the higher the atomic weight of the element, and are wholly independent of its state of chemical combination. Most of the elements give out characteristic X rays of two different wave-lengths, and when these are analyzed by an X ray spectrometer, they form the "X ray spectrum" of the element in question.

Why X Rays Penetrate "Opaque" Bodies. — It is the extreme "sharpness," or very high frequency, of the gamma and X rays which chiefly distinguishes them from ordinary light, and which gives them their special power to penetrate solid bodies which are opaque to light. Bodies absorb light only because their atoms are able to respond, or "resonate," to the vibrations in the light wave (see Section 41). But when these vibrations are very rapid — or, what means the same thing, when the "kinks" are very short — the atoms of the substance cannot respond with sufficient quickness, and hence the light is not absorbed. There is some question as to whether this explanation holds exactly on the quantum theory of radiation. However, there is doubtless also a specific relation between frequency, as such, and degree of absorption, since certain bodies strongly absorb X rays of one frequency and not of others.

The Corpuscular Properties of X Rays. — Certain physicists, among them W. H. Bragg, formerly supported the view that the gamma and the X rays are not waves but are moving particles. The reason for this advocacy lay in the fact that these rays, in passing through matter, behave as if their energy were concentrated in very minute, moving regions, instead of being spread out over a continuous "wave-front," as light energy is supposed to be in the classical theory. However, as we have seen in Section 54, latter-day developments have proved that ordinary light has the same sort of distribution, so that

Plate V

COOLIDGE X RAY TUBE

This is a modern, high power X ray tube. The upper electrode, inside of the bulb, is heated electrically. Owing to the tendency shown by all heated metals to give off electrons, this greatly increases the intensity of the cathode discharge, when the electrode is connected with a source of high potential. The " anticathode," which is shown in the center of the tube, stops the stream of electrons, and this sudden cessation of their motion causes the X rays, which are emitted from the anticathode surface in all directions.

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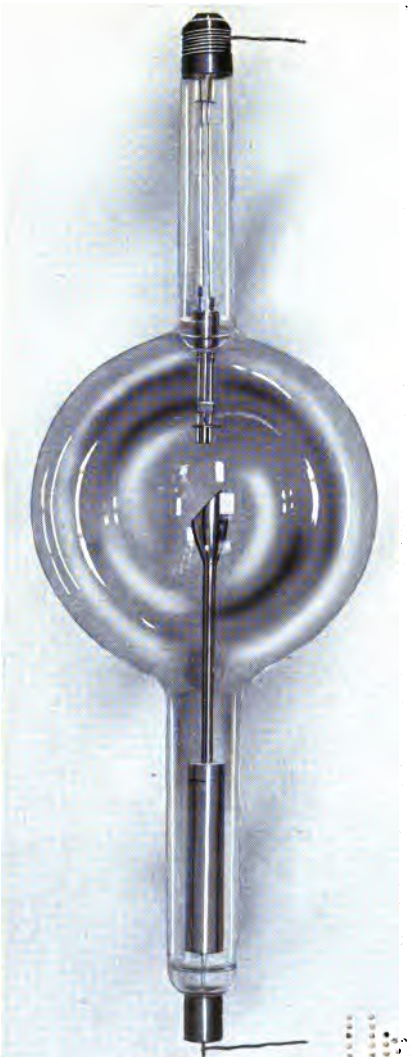

the evidence in question counts no more against the wave-theory of X rays than it does against that of light in general. Recent developments, briefly discussed in Part I, have completely converted Bragg and his school to the wave theory or at least to the general theory of radiation.

The Reflection and "Diffraction" of X Rays by Crystals. — The reflection of X rays from a crystal surface is somewhat different from that of ordinary light. The reason for this is to be found in the fact that although the atoms of the crystal are regularly arranged, they are still so far apart compared with the wave-length of the rays that the discontinuities produce a sensible effect. In Chapter VI of Part I the reflection of ordinary light has been explained as due to the generation of a return wave by the electrons of the atoms in the surface of a body which is struck by light. This is what occurs also in the case of X rays, but owing to their penetrative power and relatively short wave-length the return waves from different planes of atoms in the crystal do not fuse with each other harmoniously, except in certain favorable directions.

In other directions there is interference, that is, the waves from one layer of atoms oppose those from another layer and wipe them out. In fact, the X rays are so short that the atoms of the crystal form for them a "diffraction grating," similar in action to the mechanically ruled gratings used to bring about the interference of ordinary light waves.

Now, the direction in which interference does not take place in the case of X ray reflection depends upon the wave-length of the rays. Consequently, if we measure the angle at which the reflection of a given set of rays occurs most readily, and if we know the structure of the crystal, we can calculate the wave-length. Conversely,

using rays of known wave-length, we can deduce the structure of a crystal with the constitution of which we are not familiar. (See Figure 27.)

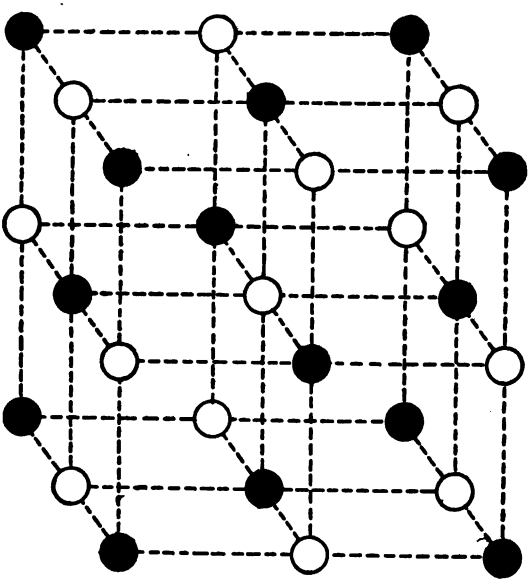

Fig. 27

STRUCTURAL PLAN OF A SIMPLE CRYSTAL

This drawing represents the structure of a crystal of potassium chloride, a substance similar to ordinary salt, as deduced from its action upon X rays. The dark spheres represent chlorine atoms, the light ones atoms of potassium. It will be seen that the unit of structure of the crystal is the individual atom, since all of the atoms are equidistant from their immediate neighbors. For the sake of clearness, the spaces between the atoms have been exaggerated, as compared with their diameters.

There are always a number of different ways in which geometrical plane surfaces can be drawn through the atoms in a crystal, and each of these theoretical surfaces is capable of reflecting or diffracting X rays. The result is that if a beam of rays is sent into a crystal, it is partly

split up into secondary beams which take different directions, characteristic of the inherent planes of the crystal atoms. When these latter beams are caught upon a photographic plate a pattern is produced from which the constitution of the crystal can be inferred.

REFERENCES

Concerning the X rays see: C. W. C. Kaye's "X Rays" (1914); and W. H. and W. L. Bragg's "X Rays and Crystal Structure," (1915). Also: S. P. Thompson's "Radiation" (1898), Chapter III. Bragg's arguments with reference to the corpuscular properties of the rays are given in Norman Campbell's "Modern Electrical Theory," second edition (1913), pp. 292–304.

Section 56

LIFE AND CATALYSIS

Living bodies are complex mixtures of active chemical substances. These substances are constantly reacting with each other and as a consequence the bodies in question would soon be destroyed if it were not for the fact that the chemical changes are so organized and controlled as to ultimately bring compensation for the destruction which they cause.

This control and regulation which is so characteristic of the activities of living beings probably depends in the last analysis upon a purely chemical principle called *catalysis*. This principle implies that the mere presence, in chemical mixtures, of very minute quantities of certain substances, can determine the nature of the changes which take place in these mixtures. Controlling substances of this sort are called *catalyzers*. The effects which they produce can be explained in terms of atoms, molecules and electrons.

The catalyzers which control the life processes in different organisms are characteristic of these organisms, and are undoubtedly transmitted to them from their progenitors through the germ-cells from which they originally developed. The reason why certain catalyzers and not others have been constantly transmitted from parent to offspring through many generations is to be found in their special power to regulate the chemical changes in organisms so as to permit the survival of the species. In other words, the present physical and chemical structure of organism must be explained not only in terms of atoms and molecules but also in terms of the history of living matter upon the earth.

The most important elements in the constitution of living organisms are carbon, hydrogen, oxygen, and nitrogen, although many others are essential. These elements are combined, usually, to form "colloidal" systems of particles (see Section 3), and many of the fundamental peculiarities of living things depend upon those of colloids.

Organic catalyzers are called *enzymes*, and on the above theory, enzyme action explains the mystery of *heredity*.

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END OF PART TWO

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